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RETROFIT DESIGN METHODOLOGY BASED ON PROCESS AND PRODUCT MODELING

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Cette thèse intitulée:

RETROFIT DESIGN METHODOLOGY BASED ON PROCESS AND PRODUCT MODELING

présentée par: JANSSEN Mathias Jacobus Margaretha
en vue de l'obtention du diplôme de: Philosophiae Doctor
a été dûment acceptée par le jury d'examen constitué de:

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I realized that design is a signal of intention.

William McDonough (1951–)

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RÉSUMÉ

L'industrie canadienne des pâtes et papiers fait actuellement face à de nombreux défis. La compétition des usines situées dans des pays où les coûts de production sont bas et les économies d'échelle avantageuses, l'augmentation continuelle des coûts énergétiques et du coût de fibres et la fluctuation des taux de change, entre autres, font qu'il est de plus en plus difficile pour les compagnies papetières canadiennes de survivre dans le marché mondial. De plus, à cause de sa nature énergivore, l'industrie a un impact environnemental important avec lequel il faut composer ce qui l'oblige à repenser sa stratégie à long terme et à envisager des objectifs de développement durable afin d'assurer sa survie et de prospérer dans le futur.

L'implantation des systèmes de gestion de données et de gestion de l'information dans les usines papetières a rendu disponibles d'énormes quantités de données reliées tant aux procédés, aux coûts qu'à l'environnement. La disponibilité de ces données et leur utilisation efficace ont accru de façon significative l'intelligibilité des processus de production et de gestion d'affaires dans les usines papetières. Il a aussi été établi que ces données n'ont pas été exploitées à leur plein potentiel et que de ce fait, il y avait place à l'amélioration. La conception de procédés en rétro-installation est un des domaines qui peut tirer parti de l'amélioration de lútilisation des données disponibles.

L'objectif de cette thèse est de développer une méthodologie pour la prise de décision reliée à la conception en rétro-installation qui utilise les données relatives aux procédés, aux coûts et à l'environnement obtenues des systèmes de gestion de l'information et en en extrait l'information et la connaissance à l'aide d'outils d'ingénierie des systèmes de procédés. Cette méthodologie sera appliquée à une étude de cas qui considère l'augmentation de la production de

pâte désencrée et l'implantation de la cogénération dans une usine intégrée de papier journal.

Cette méthodologie utilise une approche ascendante novatrice par laquelle les données de procédés et de coûts sont d'abord utilisées afin de caractériser l'usine existante ainsi que les alternatives de conception pour sa modernisation. Cette tâche s'effectue en appliquant une approche de modélisation des coûts basée sur les opérations, qui a été développée en première partie de ces travaux. Le modèle obtenu permet de synchroniser les flux de matière et d'énergie ainsi que les coûts tout au long du procédé.

Les résultats montrent que le modèle de coûts est un outil versatile pour l'évaluation de l'opération des alternatives de modernisation à l'analyse des coûts marginaux et à l'analyse des stratégies opérationnelles. Ensuite, l'information reliée au procédé et aux coûts, obtenue via le modèle de coûts, est utilisée au niveau de la chaîne logistique par le biais des modèles de chaîne logistique et d'analyse du cycle de vie afin de déterminer les conséquences économiques et environnementales. En élargissant les frontières du système au-delà de celles de l'usine, des alternatives plus durables peuvent être identifiées. Les résultats obtenus montrent que l'alternative la plus performante au niveau du procédé n'est pas nécessairement celle qui obtient les meilleurs résultats au niveau de la chaîne logistique. De plus, les analyses de scénarios fournissent une meilleure compréhension de la performance économique et environnementale des alternatives sous diverses conditions de marché. Enfin, un panel de prise de décision multicritère est réalisé afin d'évaluer systématiquement les alternatives et d'établir laquelle est préférable à l'aide de critères au niveau du procédé et de la chaîne logistique. Spécifiquement, il a été demandé au panel de pondérer les critères selon une méthode de compromis ("trade-off method"). Les résultats de ce panel indiquent que l'utilisation conjuguée des critères provenant des procédés et de ceux provenant de la chaîne logistique aboutissent à une décision différente que celle obtenue si l'on utilise seulement des critères économiques comme ceux de profitabilité, comme c'est habituellement le cas dans des études technico-économiques conventionnelles. La méthodologie complète transforme donc les données provenant du procédé en information et en savoir utile pour la prise de décision tant pour le procédé que pour la chaîne logistique.

Les travaux futurs incluent l'établissement d'indicateurs traduisant la sensibilité ou le risque dus aux variations des paramètres de conception et des conditions du marché. De plus, les considérations sociales doivent être incluses dans l'analyse afin de permettre aux décisionnaires de prendre des décisions répondant aux critères du développement durable.

ABSTRACT

The Canadian pulp and paper industry currently faces many challenges. Competition from mills in countries with low production costs and advantageous economies-of-scale, the increasing price of energy, increased fibre costs and currency exchange rates, amongst others, are making it increasingly difficult for Canadian pulp and paper companies to survive in the global market place. Moreover, due to its energy-intensive nature, the industry has a large environmental footprint that needs to be dealt with. This requires the industry to rethink its strategic goals and consider sustainability in order to survive and prosper into the future.

The implementation of data and information management systems at pulp and paper mills have made available massive amounts of process, cost and environmental data. The effective use and availability of these data have increased insight into the production and business processes at pulp and paper mills. It has also been established that these data have not been fully exploited and as such, there is room for improvement. Retrofit process design is one of the fields that may reap the benefits of improving the use of the available data.

The objective of this thesis is to develop a methodology for retrofit design decision making that uses process, cost and environmental data available from information management systems and extracts information and knowledge from them through the application of process systems engineering tools. The methodology is applied in a case study that considers the increase of de-inked pulp production and implementation of cogeneration at an integrated newsprint mill.

The methodology uses a new, bottom-up approach whereby process and cost data are first used at the process level in order to characterize the existing mill as well as the retrofit design alternatives. This is done by applying an operations-

driven cost modeling approach that was developed as part of this work. The resulting cost model is able to synchronize the process and cost flows along the process.

The results show that the cost model is a versatile tool for evaluating the manufacturing operations of the design alternatives by means of marginal cost analysis and analysis of operational strategies. Next, the process and cost information obtained from the cost model is used at the supply chain level using supply chain and life cycle assessment models in order to determine both economic and environmental consequences. By expanding the system boundaries beyond the mill fence, more sustainable alternatives may be identified. The results show that the best performing alternative at the process level is not necessarily the same at the supply chain level. Furthermore, scenario analyses give further insight with regards to the economic and environmental performance of the alternatives under different market conditions. Finally, a multi-criteria decision making panel is carried out in order to systematically evaluate the design alternatives, establishing the preferred one based on selected process- and supply chain-level criteria. Specifically, the panel members were asked to weight the criteria using a trade-off method. The result of this panel indicates that the use of both process- and supply chain level criteria leads to a different decision than would be expected by only using a single economic criterion such as profitability, as is usually done in conventional techno-economic studies. The complete methodology thus transforms process-level data into process- and supply-chain level information and knowledge for retrofit design decision making.

Future work includes the establishment of sensitivity- or risk-based process- and supply chain-level metrics, so as to capture the variation in design parameters and market conditions. Furthermore, social considerations need to be included in the analysis to enable the decision makers to make sustainable decisions.

CONDENSÉ EN FRANÇAIS

L'émergence récente de nouvelles économies importantes a provoqué une croissance sans précédent de la consommation. Afin de garantir un développement plus durable, les indicateurs de croissance économique traditionnels ne sont plus les seuls qu'il faut considérer au cours des différentes étapes de la prise de décision. Il faut désormais porter attention aux conséquences sur l'environnement et sur la société des actions à poser.

Par nature, l'industrie papetière est énergivore et a besoin de disposer d'importants capitaux, ce qui a toujours représenté pour elle une problématique. Les capitaux sont dépensés pour acquérir ou moderniser des usines afin de consolider la position de l'industrie. L'utilisation d'énergie de l'industrie a un effet environnemental significatif et l'augmentation du coût de l'énergie a affecté sa profitabilité et sa compétitivité. Malgré tout, l'industrie a un grand potentiel pour la fabrication de produits plus verts puisque ceux-ci sont largement basés sur des matériaux renouvelables. Par exemple, l'utilisation accrue de biomasse et de fibre recyclée pourrait créer une industrie plus durable.

L'utilisation des technologies de l'information dans l'industrie papetière, grâce à l'implantation des systèmes de gestion de l'information et des données, a rendu disponible de grandes quantités de données de procédés, d'affaires et environnementales. La disponibilité et l'utilisation efficace de toutes ces données a permis une meilleure compréhension des procédés de fabrication et des procédés d'affaires qui surviennent dans les usines de pâtes et papiers. Une des opportunités découlant de l'utilisation efficace de données réside dans la conception de procédé , qu'il s'agisse de rétro-installation ou de nouvelle construction.

Traditionnellement, la prise de décision en conception n'a qu'un objectif: accroître la rentabilité de l'entreprise. Dans une telle approche, les réglementations environnementales ne servent que de contraintes. Cependant, la disponibilité de données de procédés, de coûts ou environnementales offre l'opportunité de prendre des décisions en conception plus durables grâce à l'utilisation d'outils d'ingénierie des systèmes de procédé permettant de caractériser l'impact tant économique qu'environnemental de la conception.

L'objectif de cette thèse est de développer une méthodologie pour la prise de décision relative à la conception en rétro-installation qui utilise les données de procédé, de coûts et environnementales obtenues des systèmes de gestion de l'information et en extrait l'information et la connaissance grâce à l'application d'outils d'ingénierie des systèmes de procédé. La méthodologie est appliquée dans une étude de cas qui considère l'augmentation de la production de pâte désencrée et l'implantation de cogénération dans une usine intégrée de papier journal.

La méthodologie comporte trois principales étapes. Premièrement, le procédé en place et un ensemble d'alternatives sont caractérisés au niveau du procédé. Deuxièmement, l'information obtenue du procédé est utilisée dans les modèles au niveau de la chaîne logistique afin de déduire les impacts économiques et environnementaux. Troisièmement, un panel a été formé pour la prise de décision multicritère afin d'évaluer les alternatives et de choisir la meilleure alternative selon les critères fondés sur le procédé et sur la chaîne logistique. Les trois étapes sont par la suite présentées de façon plus détaillée.

La caractérisation du procédé existant et des alternatives au niveau du procédé, est réalisée à l'aide de bilans massiques et énergétiques ainsi qu'une approche nouvellement développée pour la modélisation des coûts basée sur les opérations. Cette approche définit des centres d'activité pour les procédés et pour les coûts indirects (respectivement PWC et OWC) afin de représenter les départements de production de l'usine et les ressources qu'ils utilisent. Les PWC sont définis selon les données disponibles relatives aux procédés et aux coûts et sur les changements de procédés proposés. Les PWC permettent la prise en compte de plusieurs éléments:

- Du coût et de l'écoulement massique durant le procédé
- Des critères de conception et des caractéristiques de chaque alternative ainsi que leur effet sur l'opération
- Des calculs spécifiques à chaque PWC
- De l'imputation des coûts indirects
- Du calcul des coûts basés sur les opérations selon une approche inspirée de la comptabilité par activités.

Le modèle de coûts qui en résulte est capable de synchroniser les flux de matières, d'énergie et de coûts tout le long du procédé. Le modèle est utilisé pour réaliser une analyse de rentabilité afin d'en dégager un ensemble d'alternatives. De plus, une analyse des coûts énergétiques marginaux ainsi qu'une étude sur l'efficacité énergétique sont effectuées pour les alternatives profitables. Aussi, du déplacement de la charge électrique comme stratégie d'opération est également menée pour toutes les alternatives de conception. Les résultats montrent que le modèle de coûts est un outil polyvalent pour l'évaluation des opérations des alternatives de conception.

La prochaine étape de la méthodologie est d'utiliser l'information relative aux coûts et à la production générée par le modèle de coûts basé sur les opérations pour réaliser une analyse de chaîne logistique, à l'aide de modèles d'analyse de cycle de vie et de modèles de chaîne logistique. Cette approche comme telle considère tout d'abord les changements au niveau du procédé, puis inclut les considérations de la chaîne logistique. Le modèle de la chaîne logistique permet de maximiser la profitabilité annuelle de la chaîne logistique. Il utilise l'information générée par les bilans massiques et énergétiques et l'information relative aux coûts qui correspond aux coûts de la ressource unitaire. De plus, le modèle tient compte des coûts indirects et des ajustements sont faits lorsque nécessaires. D'un autre côté, le modèle ACV n'utilise que l'information relative à la production et caractérise le changement d'impact environnemental causé par les alternatives (lorsque comparées à l'usine originale sans modification). Des scénarios ont aussi été définis afin d'évaluer la performance de la chaîne logistique des alternatives sous différentes conditions de marché sur une base annuelle. Entre autres, le prix de l'électricité ainsi que la disponibilité de la biomasse et du papier récupéré ont été considérés. Les résultats montrent que la meilleure alternative au niveau du procédé n'est pas nécessairement la meilleure alternative au niveau de la chaîne logistique. Ceci démontre l'importance d'étendre les frontières du système au-delà du procédé pour une prise de décision plus alignée avec les principes du développement durable.

La troisième étape de la méthodologie est la formation d'un panel pour la prise de décision multicritère (MCDM). Le panel évalue les alternatives de conception basées sur un ensemble de critères de décision environnementaux et économiques dont les attributs ont été calculés à l'aide des modèles de coûts guidés par les opérations et au niveau chaine logistique. Le rôle du panel est d'établir la pondération de chaque critère décisionnel, c'est-à-dire l'importance relative de chaque critère. Le panel était composé de cinq membres ayant des profils divers: deux dirigeants de compagnies papetières, un consultant en ingénierie, un expert en ACV et enfin un expert en développement durable. Quatre critères économiques (rentabilité, coût d'investissement, coûts énergétiques, profit de la chaîne logistique) et quatre critères environnementaux (santé humaine, qualité des écosystèmes, changements climatiques et ressources) ont été utilisés pour l'évaluation. De plus, une analyse de sensitivité est réalisée pour tenir compte de la différence des opinions des membres du panel quant à l'importance à attribuer à chaque critère de décision. Le résultat des travaux de ce panel indique que l'utilisation combinée des critères relatifs au procédé et de ceux de la chaîne logistique conduisent à une décision différente que celle qui serait produite en utilisant seulement un critère économique comme la rentabilité comme il est fait normalement dans les études technico-économiques traditionnelles.

Les contributions les plus importantes de ces travaux sont les suivantes:

- La méthodologie proposée utilise une approche dite ascendante pour transformer les données relatives au procédé et aux coûts en information au niveau du procédé et de la chaîne logistique et en connaissance pour la prise de décision en conception

- L'approche de modélisation des coûts basée sur les opérations, à l'aide des PWC, permet à l'usager de modéliser des alternatives de conception basées sur les données qui sont disponibles et pour les besoins du modèle

- Des analyses avancées des coûts aux fins de la prise de décision telles que l'analyse des coûts marginaux, l'étude d'efficacité énergétique et des stratégies d'opération peuvent être facilement implantées à l'intérieur d'un modèle de coûts guidé par les opérations

- L'approche ascendante proposée pour l'utilisation des données reliées au procédé et aux coûts conduit à une interprétation avancée des données à plus haut niveau (chaîne logistique). Les changements de conception en rétro-installation au niveau du procédé sont les premiers à être considérés, ensuite ceux de la chaîne logistique sont pris en compte

- Les alternatives de conception les plus durables peuvent être identifiées grâce à l'élargissement des frontières du système au-delà de l'usine lorsque l'analyse se fait au niveau de la chaîne logistique

- La réalisation d'un panel permet l'évaluation systématique d'alternatives de conception ainsi que la sélection de la meilleure alternative à l'aide des critères de décisions relatifs au procédé et au niveau de la chaîne logistique afin de sélectionner une alternative de conception
- L'analyse Monte Carlo des facteurs de pondération fournis par le panel affine l'analyse de décision. La probabilité qu'une des alternatives surpasse une autre peut être un facteur déterminant
- La décision finale peut changer à cause de l'utilisation de critères multiples au lieu de la considération unique de la rentabilité comme c'est habituellement le cas dans les études technico-économiques.

Les points suivants énumèrent quelques opportunités de recherche pour l'avenir:

- L'approche de modélisation basée sur les opérations peut être appliquée à un problème de conception pour des produits multiples comme cela pourrait être le cas dans une usine de papiers fins ou lors de l'implantation du concept de bioraffinerie dans une usine existante. Ce dernier item peut être une étude intéressante à cause de la diversité des produits qu'elle peut produire. Le modèle peut aussi être appliqué pour étudier de façon plus détaillée le coût des améliorations à apporter pour accroître l'efficacité énergétique.
- L'approche de modélisation des coûts basée sur les opérations et l'analyse au niveau de la chaîne logistique peuvent être utilisées pour générer des paramètres de risque ou des mesures de sensitivité afin de pouvoir tenir

compte des variations des paramètres de conception à l'aide des données de procédé disponibles (par exemple l'efficacité du procédé) et aussi des variations au niveau de la chaîne logistique comme entre autres la disponibilité des matières premières.

- Ces travaux n'ont pas pris en considération les paramètres sociaux dans l'évaluation de la durabilité de l'alternative de conception. Comme la durabilité a également une dimension sociale, les travaux à venir doivent inclure les mesures appropriées afin de refléter les changements sociaux qu'un projet de rétro-installation important pourrait provoquer.

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LIST OF SYMBOLS AND ABBREVIATIONS

Variables

$C^{marg,steam}$	marginal steam cost [$/GJ]
$C^{marg,power}$	marginal cost of generated power [$/MWh]
$C^{steam,tot}$	total steam cost [$]
$C^{steam,TB}$	turbine steam cost [$]
CF_n	cash flow in year n [$]
p^{steam}	steam price [$/GJ]
$P^{steam,tot}$	total steam produced by the boiler plant [GJ]
P^{power}	generated electricity [MWh]
u	utility
$U^{steam,TB}$	turbine steam usage for cogeneration [GJ]
x	attribute value

Parameters

b	intercept value of utility function $u(x)$
j	interest rate [%]
I_0	initial investment [$]
k	decision weight

K	scaling constant in the multiplicative utility function
L	plant life [y]
m	slope of the utility function $u(x)$
N	number of criteria
x^{low}	lower bound for decision attribute value
x^{up}	upper bound for decision attribute value

Subscripts

i	criteria
q	operating variant

Abbreviations

ABC	Activity-Based Costing
ABCEM	Activity-Based Costing & Environmental Management
AHP	Analytic Hierarchy Process
BAT	Best Available Technologies
DBED	Decision-Based Engineering Design
DIP	De-Inked Pulp
EIA	Environmental Impact Assessment
EMA	Environmental Management Accounting
EPC	Engineering, Procurement, Construction
ERP	Enterprise Resource Planning
HP	High Pressure
IMS	Information Management Systems
IRR	Internal Rate of Return
ISO	International Standards Organisation
IT	Information Technology

LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LP	Low Pressure
MADA	Multi-Attribute Decision Analysis
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MES	Manufacturing Execution System
MOO	Multi-Objective Optimization
MP	Mathematical Programming
NPV	Net Present Value
OMG	Old Magazine
ONP	Old Newspaper
OWC	Overhead Work Centre
PSE	Process Systems Engineering
PWC	Process Work Centre
ROI	Return On Investment
SCM	Supply Chain Management
TCA	Total Cost Assessment
TMP	Thermo-Mechanical Pulp
ToC	Theory of Constraints
VHP	Very High Pressure

CHAPTER 1

INTRODUCTION

Nature is trying very hard to make us succeed,
but nature does not depend on us.
We are not the only experiment.
Richard Buckminster Fuller (1895–1983)

1.1 Problem statement

The many technological advances and efficiency improvements of industrial processes in the recent past have not been able to compensate for the unprecedented rate of change in the consumption of goods due to the emergence of new large economies. More dramatic changes in how these goods are produced and consumed are necessary to obtain a more sustainable growth. This requires initiatives that have as a goal to not only consider the traditional economic growth indicators during the decision making stages, but also to consider the environmental and societal consequences of the actions taken.

The capital intensive nature of the pulp and paper industry has always been a major issue. The goals of capital spending are maintaining a competitive position, improving quality to increase customer satisfaction, and industry consolidation. In order to attain these objectives, capital is spent on the acquisition and modernization of mills. Furthermore, this industry is energy intensive, requiring large amounts of electricity and thermal energy for the production of pulp and paper, leading to a large environmental footprint. Also, increasing prices of fossil fuels have had a large impact on the profitability and competitiveness of the industry. Nevertheless, the pulp and paper industry may serve as an excellent platform for the production of greener products. Not only are the products largely based on renewable materials, but considering the substitution of fossil fuel by the use of biomass fuel as well as the dematerialization caused by recycling used consumer product, may lead to a more sustainable industry.

The use of information technology in the pulp and paper industry, through the implementation of mill-wide data acquisition and information management systems, has made available vast amounts of process, business, and environmental data. The availability and effective use of all these data has resulted in increased insight into both the production and business processes that occur in a pulp and paper mill. One of the opportunities stemming from the effective use of data lies within the field of process design, be it retrofit or "greenfield" design. The traditional design process in heavy industry is based on an approach where the incentives come from the upper management of a company, and are based on market trends, core business focus, ROI objectives, etc. (Figure 1.1). These incentives are delegated to mill engineers on-site, who will in turn collect the appropriate data to solve the design problem. This results in a decision making process that has only one objective: to increase the economic profitability of the company. Environmental regulations serve only as constraints in such a design approach. However, the availability of all these data at the mill level

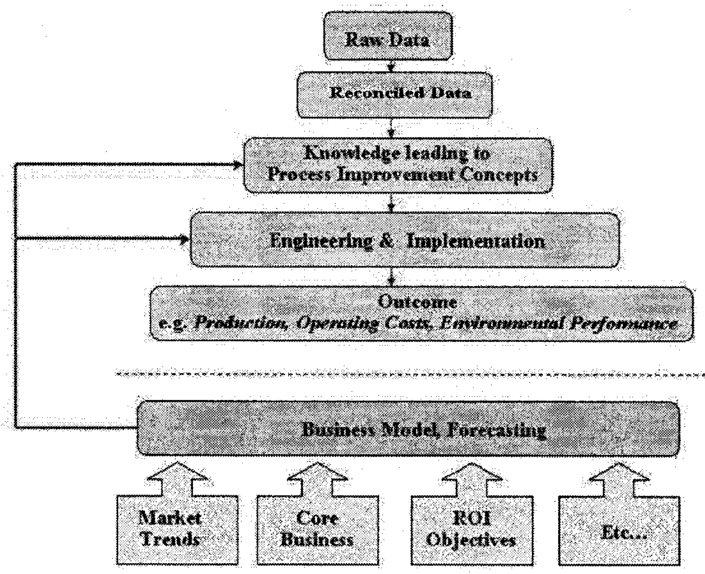

Figure 1.1: The traditional design process in heavy industry

provides an opportunity to make more sustainable design decisions by using process systems engineering tools to calculate and use decision metrics that reflect the economic and environmental characteristics of a design alternative.

A framework for design decision making that uses the available data may help managers select the preferred design alternative based on both economic and environmental objectives. The goal of this research is therefore to define such a framework and a methodology that brings together cost, process, and environmental models that reflect changes at both the process and the supply chain level. The process is modeled based on mass and energy balances and the costs are modeled using an operations-driven cost modeling approach that is based on the principles of Activity Based Costing (ABC). At the supply chain level, the supply chain is modeled and Life Cycle Assessment (LCA) is used to model the environmental impact along the supply chain. The most important outcomes of these models are then selected as criteria for decision making using a Multi-

Criteria Decision Making (MCDM) panel.

1.2 Objectives

The title of this doctorate is "Retrofit design methodology based on process and product modeling". The main hypothesis of this work is:

> ***Given the growing availability of data with the emergence of Information Management Systems, more sustainable designs can be identified in the early process design phase by employing decision criteria that are calculated using operations-driven process systems engineering tools.***

The sub-hypotheses divide this main hypothesis into three parts that are addressed in this work, i.e. process-level cost modeling, supply chain-level analysis and a Multi-Criteria Decision Making (MCDM) panel:

- ***Process level:*** *An operations-driven cost modeling approach based on Activity Based Costing-like accounting principles, reconciles process and cost data, and can be used to better reflect mill operations for marginal cost analyses suitable for retrofit design decision making*
- ***Supply chain level:*** *Expanding the scope of the design problem by including life cycle assessment and supply chain models leads to a more complete set of metrics for the identification of more sustainable retrofit design alternatives*
- ***Design methodology:*** *A multi-criteria decision making panel is effective for selecting the preferred retrofit design alternative using process- and supply chain-level metrics that are calculated using process systems engineering tools.*

The problem statement and hypotheses require that a methodology be developed in order to demonstrate the benefits of the proposed design decision making framework. This is done using a case study that considers the implementation of increased de-inked pulp production and cogeneration at an integrated newsprint mill, and addresses the following objectives:

- To build a methodology that uses a set of process systems engineering tools in order to make better design decisions based on process and cost data
- To develop and apply an operations-driven cost modeling approach in order to better analyze the operations of retrofit process design alternatives
- To use life cycle assessment and supply chain models in order to obtain a broader viewpoint on the design problem that leads to more sustainable design decisions
- To carry out a Multi-Criteria Decision Making panel whose goal it is to identify the preferred design by determining the trade-offs between environmental and economic criteria.

1.3 Thesis organization

This thesis is organized as follows : first, the relevant literature is reviewed and the gaps in the body of knowledge are identified. Next, the overall methodology in this work is presented, and the case study and its background are described. This case study is situated at an integrated newsprint mill and considers the implementation of increased de-inked pulp production and cogeneration. This is followed by a synthesis of the results that were obtained in order to demonstrate the use of the developed methodology. Furthermore, the novel aspects of this methodology are identified based on these results. Then, the various steps of the methodology are discussed and finally, the contributions to the body of knowledge are enumerated and directions for future work are given.

CHAPTER 2

LITERATURE REVIEW

It is no good to try to stop knowledge from going forward.
Ignorance is never better than knowledge.
Enrico Fermi (1901–1954)

2.1 Use of data and information in the pulp and paper industry

2.1.1 Information technology in the pulp and paper industry

With the introduction of mill-wide information technological systems in the pulp and paper industry, massive amounts of data are being collected. These data can be used to facilitate daily decision making for process troubleshooting or to improve longer term, strategic decision making, e.g. major capital spending.

Shaw (1999) surveyed Information Technology (IT) managers at the mill and/or corporate level and mill managers, and stressed the importance of IT and data availability in the pulp and paper industry. Although respondents reported an increase in the use of information systems, there was little indication of any advanced use of the acquired data in the pulp and paper industry. Using data acquisition software such as Osisoft's PI system (http://www.osisoft.com) to view the gathered data, the largest impact of using these systems was with respect to process troubleshooting, i.e. making meaningful corrections in time to increase productivity and product quality (Fadum, 1996).

Not only the mill production processes benefit from the implementation of information systems. Information technology and on-line data also have value for doing business in the pulp and paper industry, e.g. through the implementation of e-business practices and the validation of business data (Jackson & Kennedy, 2000).

2.1.2 Process and business information systems in the pulp and paper industry

The link between IT and process control for exchanging data and information is fairly obvious. For instance, Internet-based systems have been employed with the goal of managing process control across multiple sites. Full integration of IT and process control is feasible, but there are barriers such as cost, efficiency of multiple vendors working together, use of communication protocols, and data security. Both operations and process design improvements may benefit from this integration which will proliferate knowledge throughout the mills (Rooks, 2000; Sena, 2003).

McDermott (2002a) discussed ways to obtain value from IT investments and distinguished between value at the plant and enterprise levels. Plant-level systems derive their value from their ability to determine, monitor, and control processes, whereas the enterprise-level systems add value on the business and planning side of the operations. The industry focus has mainly been on the plant level in order to enhance information flow within the mills (McDermott, 2002b). A Manufacturing Execution System (MES) is an example of an application that focuses on the plant level. An MES includes detailed scheduling, production tracking, document control, and other product-oriented tasks (Scharpf, 1999).

Recently, companies have started to shift their focus towards automating information flow with customers and suppliers. McDermott (2003) argued that the value of IT solutions increases as they become more tightly integrated, and as a result, pulp and paper companies move towards a closer collaboration with their business partners. Supply Chain Management (SCM) and Enterprise Resource Planning (ERP) systems play a major role in connecting enterprises with customers and suppliers.

An ERP system is an integrated system that includes human resources, inventory management, accounting, and production planning (Scharpf, 1999), and is seen as an important tool for managing the business of a company. Yet, these systems have not been widely implemented in the pulp and paper industry (Shaw, 2000; Janssen, Laflamme-Mayer, Zeinou, & Stuart, 2004). The main reason is that there are considerable gaps between paper industry needs and ERP functionality. These gaps relate to the specific nature of the manufacturing process in a pulp and paper mill (Lail, 2000). Figure 2.1 shows specific application areas and the corresponding degree of fit with ERP. Manufacturing applications such as block scheduling and product tracking, which are crucial for pulp and paper mills, are extremely difficult to fit into an ERP system.

SCM is the process of keeping organizational, supply, and customer issues compliant with customer needs (Hagy, 2000). SCM has not penetrated the pulp and paper industry extensively, mainly because of the conservative attitude of the

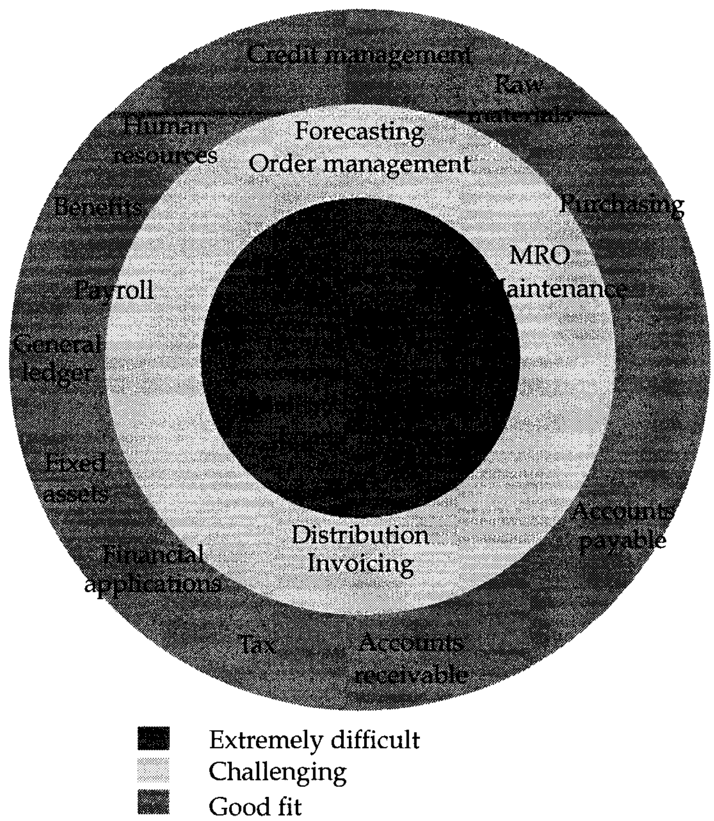

Figure 2.1: ERP/paper industry applications–degree of fit (from Lail (2000))

industry towards new technology, the individualistic views of mills, and the complex relationship between mills and suppliers (Bottiglieri, 2000). Also, most mills have not obtained greater insight into supply chain issues via information systems (Shaw, 2000; Janssen et al., 2004).

2.1.3 Data usage at pulp & paper mills

Two recent surveys on the use of Information Management Systems (IMS) in the pulp and paper industry (Janssen, Laflamme-Mayer, & Stuart, 2003; Janssen et al., 2004) indicated that mills recognize the advantages of using IMS. Several

Table 2.1: Applications of information management systems (IMS) in the pulp and paper industry

Mill	Application
Alabama River Pulp Co. Inc. (Perdue Hill, AL)	Processes are better synchronized, performance is tracked, and process problems are better characterized
Abitibi-Consolidated Inc. (Jonquière, QC)	Instrument and control loop integrity are verified, and routine maintenance tasks are streamlined
Abitibi-Consolidated Inc. (several mills, ON)	Power consumption is monitored and planned to decrease cost in a deregulated power market
Madison Paper Industries (Madison, ME)	Business processes are supported and the financial performance is tracked in real time
Tembec Inc. (11 mills in US and Canada)	Improving reliability and less parts inventory, benchmarking of the mills against each other

applications of information systems implemented at pulp and paper mills have been reported (Yeager, 1998; Anon, 2002; Roussel, 2003; Shaw, 1998, 2003, 2006) (Table 2.1). However, the available data are not yet fully exploited, although increased data availability has enhanced the *ad hoc* capability of problem solving and targeting ROI opportunities (e.g. increase of productivity and efficiency, and product quality) (Figure 2.2). Lack of resources (time and money) and knowledge were the main barriers for extracting more information from the data.

2.1.4 Data interpretation using process systems engineering tools

The on-line process and business data that have become available due to advances in IT have not been fully exploited in the pulp and paper industry, and significant improvements can be made. So far, the on-line data have mostly been used to track, trend, and troubleshoot the processes from which the data are taken. A certain problem is approached by characterizing the problem, followed by gathering the necessary data to find a solution. The data is visualized in graphs to obtain the essential information, and to react to the occurring problem, but it is not manipulated for interpretation at a more global level. The use

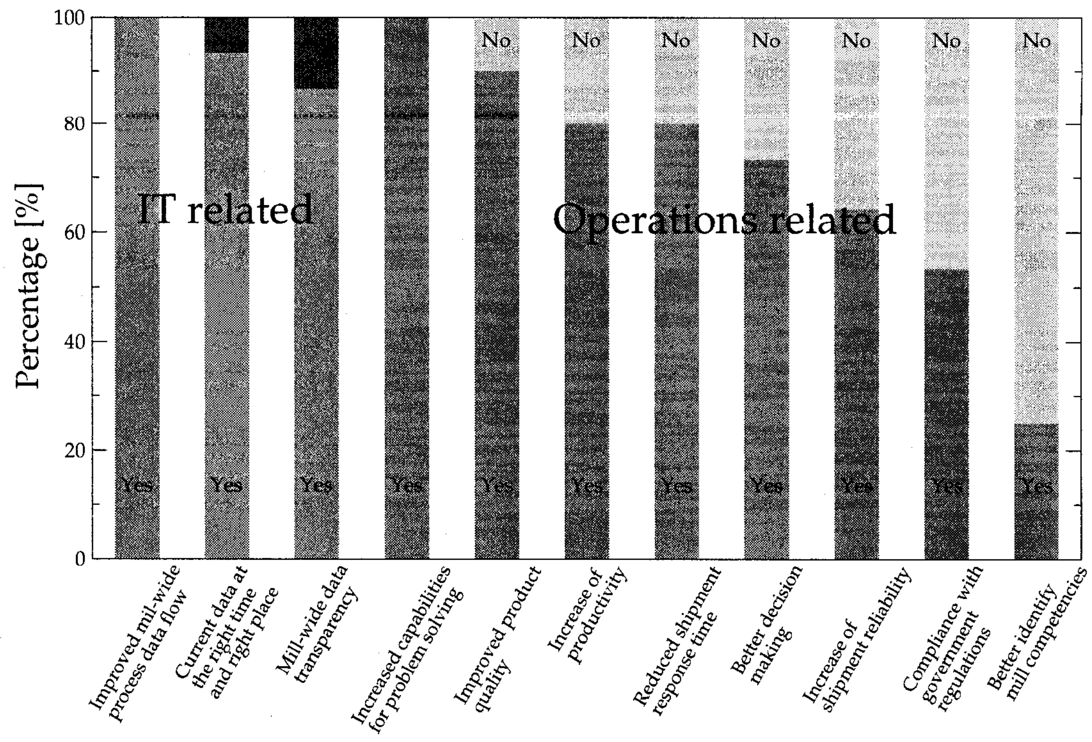

Figure 2.2: Impact and benefits of the implementation of information management systems (IMS) (adjusted from Janssen (2004))

of more advanced tools such as Process Systems Engineering (PSE) tools, e.g. optimization, supply chain modeling or Life Cycle Assessment (LCA) are able to interpret data at this level but have not been widely adopted. Furthermore, both process and business data can be used for process operations or retrofit design analysis, but the emphasis has been on using process data. There has been little effort to develop an analytical approach that integrates the different kinds of data in a modeling framework and that enables the user to exploit the available process-level data by interpretation at a higher level using PSE tools.

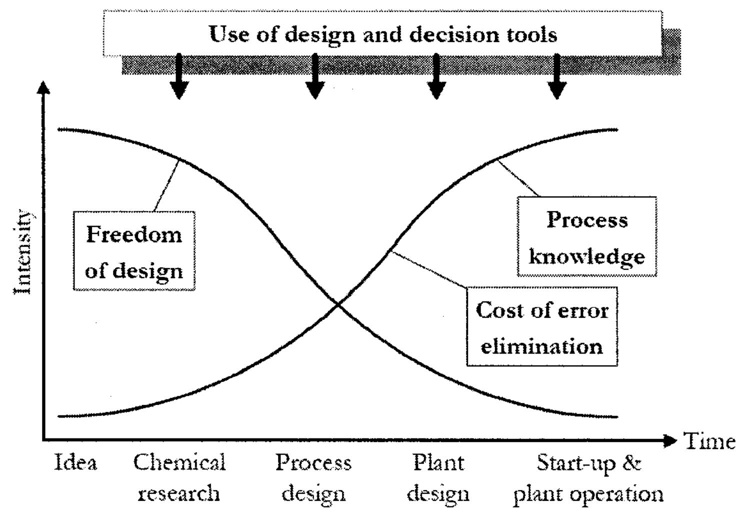

Figure 2.3: Evolution of degrees of freedom, process knowledge and cost of error elimination for process development (from Uerdingen (2002))

2.2 Overview of current design practices

2.2.1 Greenfield vs. retrofit process design

Greenfield process design is part of the development of a new process that starts with the decision to manufacture a (new) product and ends with the start-up and operation of this process (Figure 2.3) (Uerdingen, 2002). The greenfield process design step generates and evaluates several design alternatives and subsequently the most promising designs are chosen for more detailed evaluation. The most important decisions have to be taken early in the process development, when the least process knowledge is available. These decisions therefore have the biggest impact on the final capital investment needed to implement the design (Steinberger, 1995).

Retrofit process design is considered when the operation of the process or other internal and external conditions make it necessary to adjust the process (Uerdingen, 2002). Examples of such conditions are technology evolution, environmental regulations, increased energy prices and competitive strategy considerations. Fisher *et al.* (1987) gave the following definition for retrofitting:

> "By retrofitting we mean making minor changes in the structure of a flowsheet and/or some equipment sizes in order to:
>
> a) significantly reduce operating costs
>
> b) increase the capacity of the process
>
> c) process new feedstocks
>
> d) incorporate a new technology."

This can be achieved by process debottlenecking, expansion of equipment capacity to ease constrained operations or modification of equipment to lower operating cost. However, more radical process changes may be necessary, e.g. the expansion or shutdown of complete production lines, when the external conditions of the plant change dramatically. Retrofit process design can be considered as a tool for improving operation of an existing process design, whereas greenfield process design conceives a completely new process. Grossmann *et al.* (1987) mentioned several differences between retrofit and greenfield process design:

- Greenfield design has many more degrees of freedom in the preliminary phase. This means that the preliminary design and selection and sizing of equipment can be done independently, whereas in retrofit design this needs to be done simultaneously. As a result, retrofit process design is more constrained than greenfield process design and needs to take into account the influence changes in one process of a plant may have on the other parts of this plant.

- Retrofit design problems need much more complex models in order to describe the performance of the existing equipment, which may run far from nominal conditions. Greenfield design only needs models that characterize nominal conditions.

- The possible alternatives in retrofit design are much larger than for greenfield design. This is a result of both considering the tasks of the design and the existing equipment alternatives within which to accomplish them.

2.2.2 Design practices in the pulp and paper industry

The pulp and paper industry is one of the most capital intensive industries and therefore high capital effectiveness is crucial. In the past, the focus of large capital projects was on productivity and capacity expansion, but under the current economic circumstances such projects may not be capital effective. Rather, the focus has shifted to improved product quality, use of low cost raw materials and flexible product development. When rolling out a large project using the EPC (Engineering, Procurement, Construction) approach, the scope definition is the most critical and if well executed, it prevents schedule and cost overruns which is crucial for commodity industries. Due to downsizing technical and engineering staff, EPC has been employed by pulp and paper companies by contracting third-party companies (Forbes, 2000). Pre-feasibility design (or techno-economic) studies can be considered as a part of EPC. However, in practise they have not been part of this approach, resulting in a disconnect of the analysis of design alternatives. This is due to the fact that the prefeasibility study is typically carried out by the owner (the mill), while the EPC study is done by 3rd party engineering/construction companies.

Pre-feasibility studies for process design in the pulp and paper industry, be they

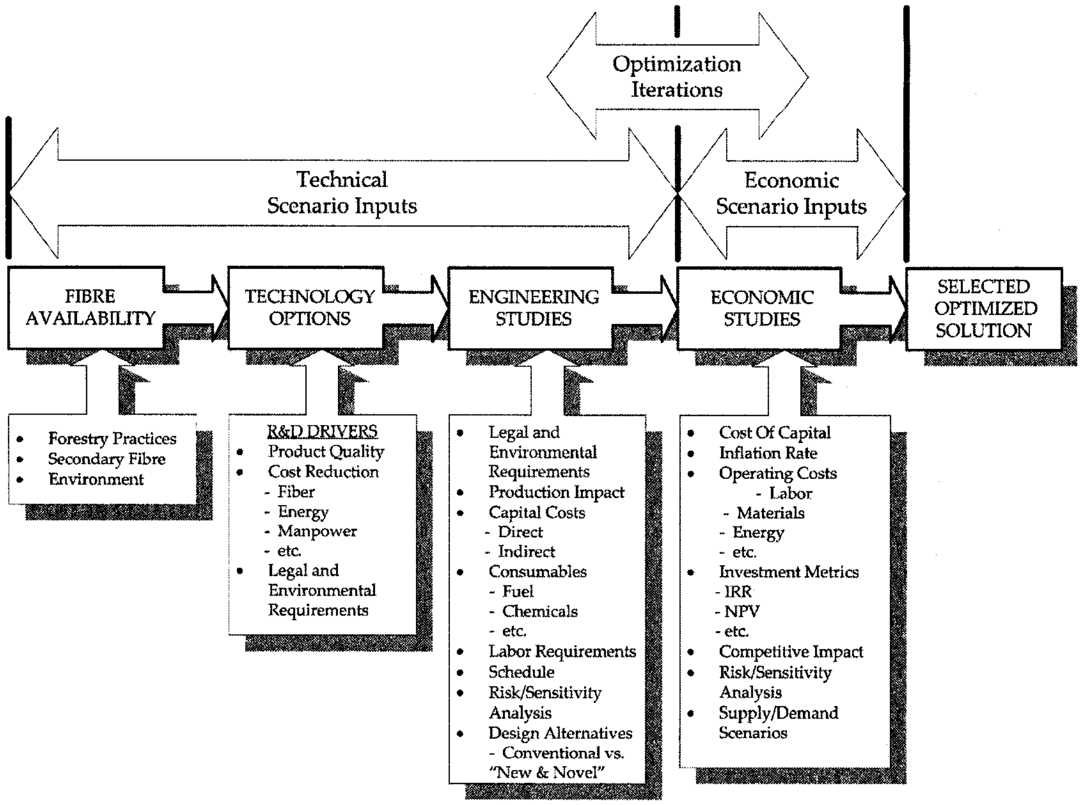

Figure 2.4: Approach to carrying out a standard techno-economic analysis in the pulp and paper industry

greenfield or retrofit, have mostly been carried out by following the procedures of a standard techno-economic analysis. This mostly resulted in a limited number of process design alternatives being taken into account for further economic analysis. The cost estimates for these alternatives under study have often been based on the knowledge and expertise of the engineer or engineering team.

In a standard techno-economic analysis in the pulp and paper industry, technical and economic scenario inputs are used to determine an optimized solution (Figure 2.4[1]). When examining these inputs more closely, it is apparent that the drivers for technological enhancement and pre-feasibility engineering are

[1]Source: Kevin Riemer, KNRconsult, Montréal (2005)

mostly based on reducing costs as well as on meeting environmental and legal requirements (Cody, 2003; Shaw, 2002). Cost reduction is the objective used for determining the optimal solution, whereas the legal and environmental requirements are used as the constraints on the feasibility of a design alternative. This reflects the role of environmental management in the traditional strategic planning process: only environmental compliance is considered. Both conventional and new technologies are considered, and an analysis can be executed to quantify the risk of implementing a certain technology.

Fibre availability and procurement need to be taken into account as this influences the technology considered for producing pulp for papermaking. For instance, if secondary fibre is readily available and the cost of transportation is not prohibitive, a mill would rather implement a de-inked pulp (DIP) plant instead of, or in addition to, a thermo-mechanical pulp (TMP) plant.

During an economic analysis, the process design alternatives are evaluated over their lifetime, typically using the Net Present Value (NPV) or the Internal Rate of Return (IRR) of the project. NPV can be expressed as:

$$NPV = -I_0 + \sum_{n=1}^{L} CF_n \left(\frac{1}{1+j}\right)^n \tag{2.1}$$

where:

$$\begin{aligned} I_0 &= \text{initial investment} \\ CF_n &= \text{cash flow in year } n \\ j &= \text{interest rate} \\ L &= \text{plant life} \end{aligned}$$

The IRR is the interest rate at which the NPV is equal to zero: $NPV(j) = 0$. The NPV compares the value of a dollar today versus the value of that same dollar in the future, after taking inflation and return into account. Currently, NPV and IRR are commonplace investment metrics used in the pulp and paper industry. A disadvantage of using NPV is that it does not account for any extra investment or divestment in the future after the project decision has been made. This may considerably influence the profitability of a project (Keswani & Shackleton, 2006). Furthermore, the sensitivity of NPV to the interest rate may lead to different decisions.

Although financial risk and/or sensitivity analysis have been included in Figure 2.4, these elements are rarely incorporated in current studies. The uncertainty or volatility of prices (e.g. for raw materials) or future economic conditions could be considered by executing a risk analysis using Monte Carlo simulation (Hacura, Jadamus-Hacura, & Kocot, 2001).

Due to the energy intensive nature of the paper making process, the energy efficiency of the process has been the focus of several studies. Energy efficiency projects may be carried out to further optimize the profitability of a design alternative by, for example, reducing steam demand in the process and thus the total manufacturing cost. Pinch analysis was used for thermal optimization (Dylke, Folkestad, Retsina, & Savvakis, 2003) and for definition and organization of energy efficiency projects by reducing both energy and water use at a mill (Lafourcade, Wising, & Stuart, 2006b, 2006a).

2.2.3 Potential use of data in retrofit process design

The current retrofit design approaches do not take advantage of the process and cost data that have become available at mills. Rather, they mostly use the expertise and experience of the engineering team. The use of process and cost data helps to better characterize the complexity and performance of the existing process design and its operations, and may improve the generation and characterization of retrofit design alternatives based on such information. Provided that the information infrastructure that enables the use of all these data is available, it is imperative to develop a retrofit design approach that is able to use these data coming from plant information management systems. Such an approach would first characterize the existing process design (thus taking into account the operating conditions under which the plant equipment runs) and the retrofit design alternatives using process systems engineering tools and the available data, and then continue to use the process-level information extracted from these data at a more global level (outside the mill boundaries).

2.3 Emerging process design tools

2.3.1 Information management in the chemical process design process

Over the last 10 to 15 years several research projects in the chemical engineering field have been initiated to better describe and understand the process design process and how to use and integrate the different tools that have become available for gathering or generating information. The purpose of these tools is to improve the management of information that is used in the design process, and the support of the workflow during the design process (Westerberg, Subrahmainan, Reich, & Konda, 1997; Marquardt & Nagl, 2004). This research is essential for the optimization of the design process.

The design process consists of all the activities that a design team undertakes to tackle a design problem. Retrofit design faces special challenges such as its complexity (amount of alternatives, complex process models) (Grossmann, Westerberg, & Biegler, 1987) and resistance to change by those affected (Westerberg et al., 1997). Marquardt and Nagl (2004) itemized several weaknesses of current design practises that are related to the work processes and the software tools that are employed. A lack of documentation, little re-use of past experiences, little integration between work processes and design data and methodologies (based on mathematical models), and lack of software integration are some of these weaknesses. Furthermore, although the importance of dealing with inconsistent data was discussed (Bayer, Schneider, & Marquardt, 2000; Bayer & Marquardt, 2004), the question of how to use and reconcile data coming from different data sources in an existing plant has not been extensively addressed. New design methodologies need to take into account these issues by exploiting the availability of plant process and cost data and use these data in mathematical models that represent the various aspects of both the design problem and the design process.

2.3.2 Cost modeling

2.3.2.1 Cost management methods

Cost information has been crucial for management decision making. Management cost accounting is the discipline that characterizes, interprets and communicates cost information for internal managerial decision making. Traditional volume-based cost accounting has been criticized for not providing relevant information for decision making. Over time, various methods have emerged to improve the traditional cost accounting system. Direct costing, Theory of Constraints (ToC) (or throughput accounting) and Activity-Based Costing (ABC) have received a great deal of attention (Boyd & Cox III, 2002).

Direct costing received a lot of criticism because in theory it only includes vari-

Figure 2.5: Relationship between resources, activities, and objects in ABC (adapted from Bargmann (2002))

able manufacturing costs and may therefore lead to poor pricing decisions since overhead costs are not included. Theory of Constraints is different from direct costing in that it recognizes that direct labour often is dealt with as a fixed cost. Theory of Constraints however, is not a cost management system, e.g. it does not allocate overhead costs. Rather, it focuses on the identification and management of bottlenecks in a process and may therefore serve as a guide for identifying smaller retrofit design projects in order to optimize a process. However, for the evaluation of large strategic investments and their impact on the manufacturing cost, including overhead costs, a costing system that also encompasses the treatment of these overhead costs and any changes in the cost structure is needed.

ABC is a cost system that first accumulates overhead costs for each of the activities of an organization, and then assigns the costs of activities to the products, services, or other cost objects that caused that activity (Horngren, Sundem, Stratton, & Teall, 1999). Furthermore, it allows modeling of the usage of resources by the activities that are carried out, followed by linking the activities with the cost object (Figure 2.5). The consumption of resources by activities is quantified by a resource driver and the consumption of activities by objects is quantified by an activity driver. ABC has mostly been applied in the discrete manufacturing industry.

ABC differs from traditional volume-based costing systems in the following ways (Figure 2.6) (Emblemsvåg & Bras, 2001; Kaplan, 1994):

- Cost objects consume activities and these activities consume resources

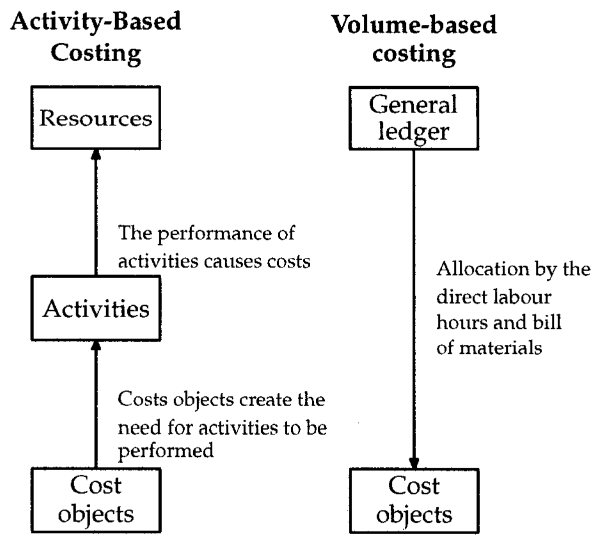

Figure 2.6: ABC vs. volume-based costing (from Emblemsvåg and Bras (2001))

- ABC uses activity and resource drivers to trace costs to cost objects in a causal manner
- ABC recognizes a cost hierarchy of indirect and support expenses, i.e. unit-level, batch-level, product- and facility-sustaining activities, whereas traditional systems only recognize unit-level activities.

ABC has a more process-oriented approach for tracing costs than the volume-based method and can be applied in a manufacturing process to better account for overhead costs. Besides a more process-oriented approach to cost modeling, ABC also leads to higher accuracy, results in better allocation of overhead costs and is able to provide better performance indicators (Bras & Emblemsvåg, 1996; Chan & Spedding, 2003; Malik & Sullivan, 1995; Shapiro, 1999; Steen & Steensland, 1994; Tatsiopoulos & Panayiotou, 2000) (Table 2.2).

ABC has been abandoned by companies because it failed to capture the complexity of operations, took too long to implement or was too expensive to build

Table 2.2: Benefits of the use of Activity-Based Costing

Authors	Application	Benefits
Bras & Emblemsvåg (1996)	Life cycle design under uncertainty	Superiority in cost tracing, separation of direct and indirect costs, higher accuracy
Chan & Spedding (2003)	Cost management in an integrated multidimensional process improvement methodology	Process-oriented
Malik & Sullivan (1995)	Determine optimal product mix and product cost in a multi-product manufacturing environment	Allocation of indirect resources
Shapiro (1999)	Combination of ABC and mathematical programming for strategic resource planning	Higher accuracy, better allocation
Steen & Steensland (1994)	Track production costs and cost variances in an integrated pulp and paper mill	Higher accuracy
Tatsiopoulos & Panayiotou (2000)	Evaluation and justifying business process reengineering	Better performance indicators, better overhead allocation

and maintain (Kaplan & Anderson, 2004). A cost model based on ABC principles therefore needs to be able to deal with such problems. Furthermore, it has been recognized that ABC is a highly data-intensive method requiring information that may not be available. As a result, a cost model based on the principles of ABC cannot always be constructed in sufficient detail because of a lack of data and information. The purpose of the model also needs to be clearly defined in order to determine the level of detail needed. Therefore, the choice of resource and activity drivers and the level of detail of the cost model should depend on its purpose and on the ease with which the necessary data can be obtained, and the amount of drivers should be properly managed (Emblemsvåg & Bras, 2001). However, the problem of data availability has been reduced significantly with the introduction of large-scale data and information management systems in the industry.

2.3.2.2 Environmental cost management methods

Several cost management methods have been developed to explicitly consider environmental costs. Activity-Based Costing & Environmental Management (ABCEM) (Emblemsvåg & Bras, 2001) and Environmental Management Accounting (EMA) (Jasch, 2006) are both closely related to ABC. Their goal is to more effectively track both the physical (mass and energy) and monetary resources that are used. Both approaches use mass and energy balances to link the available cost information to the resource use in order to improve efficiency of a process. These costing systems focus on the production process and do not consider the complete life cycle of a product. Furthermore, they do not result in providing extra information concerning the environmental impact of the different process units, i.e. it is known beforehand which units cause an environmental impact.
Life Cycle Costing (LCC) as discussed by Geitner & Galster (2000) tries to accurately determine the amount of capital needed to achieve the lowest possible life-cycle cost of a process design. This cost includes all anticipated future costs such as maintenance and decommissioning. This method does not have an environmental focus per say. Another LCC method, based on life cycle assessment, includes the product R&D, production cost, cost for the user of the produced product and end-of-life cost, i.e. it follows the product from cradle to grave (Rebitzer, Hunkeler, & Jolliet, 2003). Both LCC methods focus on cost when comparing design alternatives, but do not consider profitability of a design explicitly.
Total Cost Assessment (TCA) is another costing methodology that considers the life cycle of a product and involves a wider view on potential environmental and health (E&H) risks and costs when compared to conventional costing methodologies (Constable et al., 1999). Five types of costs are defined in the TCA methodology:

Type I : Direct costs for the manufacturing site

Type II : Potentially hidden corporate and manufacturing overhead costs

Type III : Future and contingent liability costs, e.g. fines, penalties and future liabilities

Type IV : Internal intangible costs, e.g. cost of consumer acceptance and loyalty, worker morale

Type V : External costs. These are cost that are borne by society.

TCA was designed for internal managerial decision making, particularly in situations where analyses of risks, costs and benefits are possible from many perspectives. However, there are uncertainties present in the different types of cost. In particular, type IV and V costs are hard to measure. Furthermore, type V costs do not impact the profitability of a company and should not be used for internal managerial decision making. Dow Chemical Company used TCA to address its business costs (types I to IV), and considered to use type V for public policy (Norris, 2001). The application of TCA to process design has not received much attention in the literature. Cost data from the initial report (Constable et al., 1999) have been used to calculate so-called sustainable costs based on CO_2 usage and emissions (Hertwig et al., 2002; Xu et al., 2005). These sustainable costs were characterized as external costs (type V). However, these are not costs that are borne by society, but are incurred by the company.

2.3.2.3 Marginal costing

Marginal cost analysis helps identifying operating conditions at which maximum profitability is achieved for design improvements. In marginal economics,

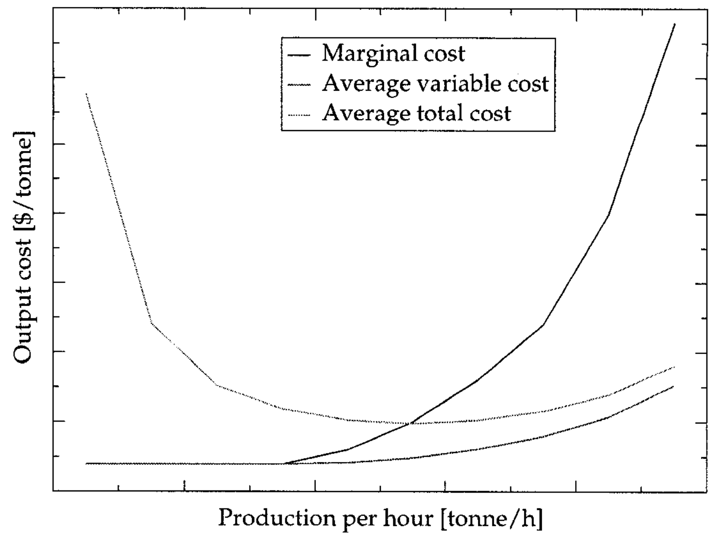

Figure 2.7: Illustration of marginal cost analysis

both incremental manufacturing costs and revenue are seen as variable. This results in a more realistic view of how costs per produced unit change, and may lead to the observation that unit manufacturing costs decrease at first, but then start to rise again (Figure 2.7). This means that there is an optimum for capacity utilization. When looking at average manufacturing costs, these incremental costs are not visible (Lail, 2003). Marginal cost analysis identifies operating scenarios that maximize the cash flow for a given investment and for different conditions. Furthermore, the use of production functions to characterize the (nonlinear) resource behaviour of the operations allows for a more accurate view of manufacturing costs and adds extra complexity (Fogelholm, 2000). In the chemical engineering literature, marginal costing has not been widely applied. As an example, Hui (2000) used marginal values of intermediate materials and utilities and their impact on profit to debottleneck a production site.

2.3.2.4 Advanced cost modeling for continuous process design

For the design of continuous processes, traditional volume-based costing has been the prevalent method to calculate operating costs. However, in order to take into account more complex operational questions for the design decision that is to be made, a more advanced cost model is necessary. ABC or ABC-like cost models provide a platform to capture this complexity.
In the literature there is generally a lack of information on describing how process design or operations parameters can be linked to cost parameters in ABC-like models for continuous processes such as paper making. The focus has mostly been on cost modeling for product development or product (re)design in discrete manufacturing (e.g. Bras & Emblemsvåg (1996), Ping Ge & Wang (2007) and Zhang & Tseng (2007)). Therefore, an operations-driven cost modeling approach based on the principles of ABC needs to be developed that focuses on the process (instead of the product) in order to obtain accurate and consistent information for retrofit design decision making. Such an approach also needs to have the flexibility to include more advanced operations analyses such as marginal cost, energy efficiency or production capacity analysis in order to capture the complexity of the process. The approach should also be capable of evaluating operational strategies.

2.3.3 Supply chain-level modeling

2.3.3.1 Life Cycle Assessment

In recent years, society has increasingly become aware of the burdens that it imposes upon the environment. Consequently, several tools have been developed to assess and quantify these burdens. One of the most popular tools is Life

Cycle Assessment (LCA). The definition of LCA according to the International Standards Organisation (ISO) is as follows (Jensen et al., 1997):

> "Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product, by:
>
> - Compiling an inventory of relevant inputs and outputs of a system
> - Evaluating the potential environmental impacts associated with the inputs and outputs
> - Interpreting the results of the inventory and impact phases in relation to the objectives of the study.
>
> LCA studies the environmental aspects and potential impacts throughout a product's life from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."

The LCA framework consists of 4 major parts that cooperate interactively (Figure 2.8):

1. Goal and scope definition: besides the goal and scope of the study, the functional unit and the system boundaries are defined
2. Inventory analysis: the necessary input and output data are collected, related to the specific system, and validated. The system boundaries can be refined

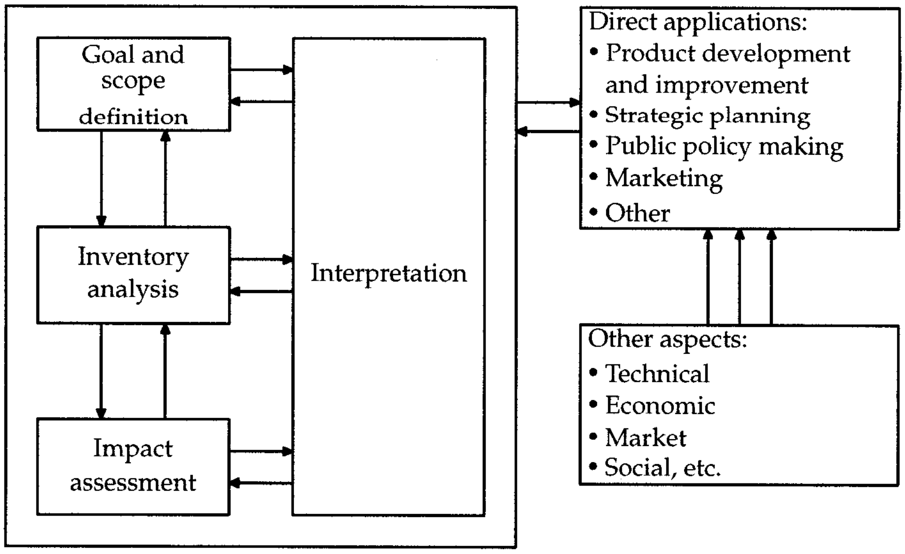

Figure 2.8: Framework for LCA (from Jensen *et al.* (1997))

3. Impact assessment: the environmental impact categories are defined, the inventory data are classified and the relative contribution of the inputs and outputs is assigned. As a last step the different categories are weighted

4. Interpretation: the significant environmental issues are identified, the whole procedure is evaluated and conclusions and recommendations are made.

LCA and chemical engineering are closely related since LCA relies heavily on mass and energy balances and can create environmental performance indicators (Chevalier, Rousseaux, Benoit, & Benadda, 2003). Therefore, it has been applied in process selection, design, and optimization for identifying clean technologies (Azapagic, 1999). LCA provides knowledge regarding environmental trade-offs. LCA has been used for the calculation of indicators that have been applied as environmental objectives for process design and optimization (Stefanis, Livingston, & Pistikopoulos, 1997; Alexander, Barton, Petrie, & Romagnoli, 2000; Diwekar, 2003). Furthermore, LCA was used to take into account the environ-

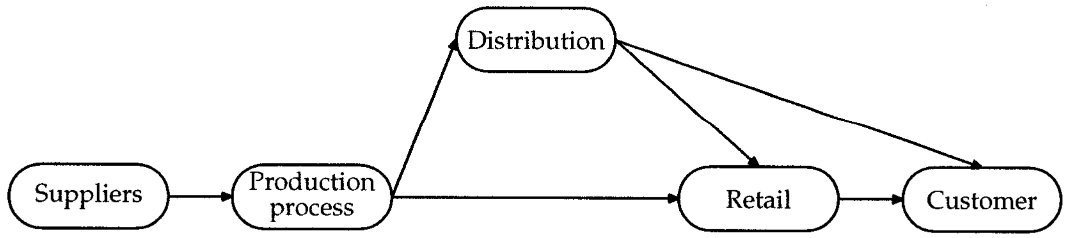

Figure 2.9: Traditional supply chain

mental performance during evolution of technology, market and environmental regulations for the identification of retrofit design alternatives (Mendivil, Fischer, & Hungerbühler, 2005).

2.3.3.2 Supply chain modeling in the chemical industry

A supply chain is (Figure 2.9) (Stadtler & Kilger, 2000):

> "a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer."

Supply chain modeling is a tool for analyzing the material flow, including logistics and inventory, in a supply chain system and subsequently for optimizing it. Shah (2005) gave an overview of supply chain design, simulation and policy analysis and planning in the chemical industry. The goal of supply chain design is to increase shareholder value by making strategic decisions concerning this design, e.g. where to locate facilities or how to change existing facilities. Greater benefit can be achieved by considering production aspects besides logistic ones, and the manufacturing complexity and efficiency of a plant. For instance, retrofit process design including the supply chain using financial and cash management objectives (Badell, Romero, & Puigjaner, 2005) and retrofit supply chain design using profit and demand satisfaction objectives (Guillén, Mele, Bagajewicz, Espuña, & Puigjaner, 2005) have been carried out. Furthermore, a systematic approach was used to identify the synergy among different process systems by looking at supply chain management aspects to overcome financial and environmental obstacles (Türkay, Oruç, Fujita, & Asakura, 2004). These applications however focused on supply chain considerations while taking into account process design. Shah (2005) remarked that process design for supply chain efficiency will be an important future research area, i.e. the focus would be on design first followed by the inclusion of supply chain-level aspects. This is an important issue since the performance of process industry supply chains is strongly affected by the flexibility and responsiveness of the production process.

2.3.3.3 LCA and supply chain modeling in the pulp and paper industry

LCA has been used in the pulp and paper industry for identifying environmental improvement opportunities in newsprint production (Salazar, Samson, Munnoch, & Stuart, 2006). Sensitivity analyses were carried out to identify process parameters that were most sensitive. Subsequently, scenarios were run that reduce the use of energy and it was shown that this improves the environmental performance along the life cycle. This work was extended by developing a methodology to integrate LCA considerations into Environmental Impact Assessment (EIA) for retrofit process design purposes (Cornejo-Rojas, Janssen, Gaudreault, Samson, & Stuart, 2005). EIA assessed the facility-based environmental impact whereas LCA assessed the environmental impact at the product level. LCA has also been used in the pulp and paper industry for comparison of products with the same function, process analysis and benchmarking, and evaluation of new products and strategic evaluation. LCA has not been integrated in the product design phase in the pulp and paper industry, because of the industry's relatively mature nature (Gaudreault, Samson, & Stuart, 2007a, 2007b). Supply chain modeling has been done in the pulp and paper industry, but the applications have mostly focused on the optimization of process operations taking into account the supply chain. For instance, Markov process decision models were used for inventory control of finished paper products (Yin, Liu, & Johnson, 2002) and for production planning under uncertainty (Yin, Liu, & Yin, 2003). Bredström *et al.* (2004) considered the supply chain planning for several pulp mills of Södra Cell AB in order to reduce the supply chain costs. Furthermore, supply chain optimization was used to allocate supplier to mill, product to paper machine and paper machine to customer and to solve a number of strategic and tactical decision problems (Philpott & Everett, 2001). Another modeling approach was proposed by Laflamme-Mayer *et al.* (2005) which integrates process and cost data gathered by an information management system at a pulp and paper mill for supply chain optimization. This so-called bottom-up approach used these data in order to represent the process capability at the higher level for supply chain decision making. The use of the bottom-up approach for supply chain management allows for a better representation of process complexity and a more accurate determination of production costs per grade. There has also been some attention for supply chain design in the pulp and paper industry. An approach to design international production-distribution networks for make-to-stock products for convergent manufacturing processes was proposed (Martel, 2005a). This approach was used to re-engineer the North-American production-distribution network of Domtar Inc. (Martel, 2005b). The approach has the flexibility to consider re-engineering of the production process through modeling of facility lay-out and capacity options. The facility lay-outs were characterized by capacity, floor space used and cost. However, the approach again focused on the supply chain considerations while taking into account process design changes.

2.3.3.4 Combined LCA and supply chain modeling

A supply chain model can be used alongside an LCA model. These models are able to calculate the economic and environmental impact beyond the boundaries of a production process, and include the impacts of suppliers (e.g. the generation of the delivered electricity, supply of recycled paper) and customers (e.g. the disposal of newspapers into landfill sites) next to that of the on-site production process. An environmental supply chain structure was defined to reflect this idea (Figure 2.10) (Beamon, 1999).
So far, combining LCA and supply chain models for the economic and environmental assessment of process design alternatives and/or operations scenarios has not been dealt with extensively. Moreover, to our knowledge this has only been done for greenfield process design. Hugo (2005) extended the Methodology for Environmental Impact Minimization (MEIM) (Stefanis, Livingston, & Pistikopoulos, 1995) for establishing the trade-off between environmental damage and economic benefit at an industry-wide level along the supply chain and for providing an environmentally conscious basis for greenfield investment planning. The NPV and the Eco-Indicator 99 score (Goedkoop & Spriensma, 2001), an aggregated environmental indicator, were used as economic and environmental objectives. Using a multi-objective MILP (moMILP) formulation, this approach yielded the optimal set of design alternatives which exhibits a clear trade-off between the economic and environmental objectives.

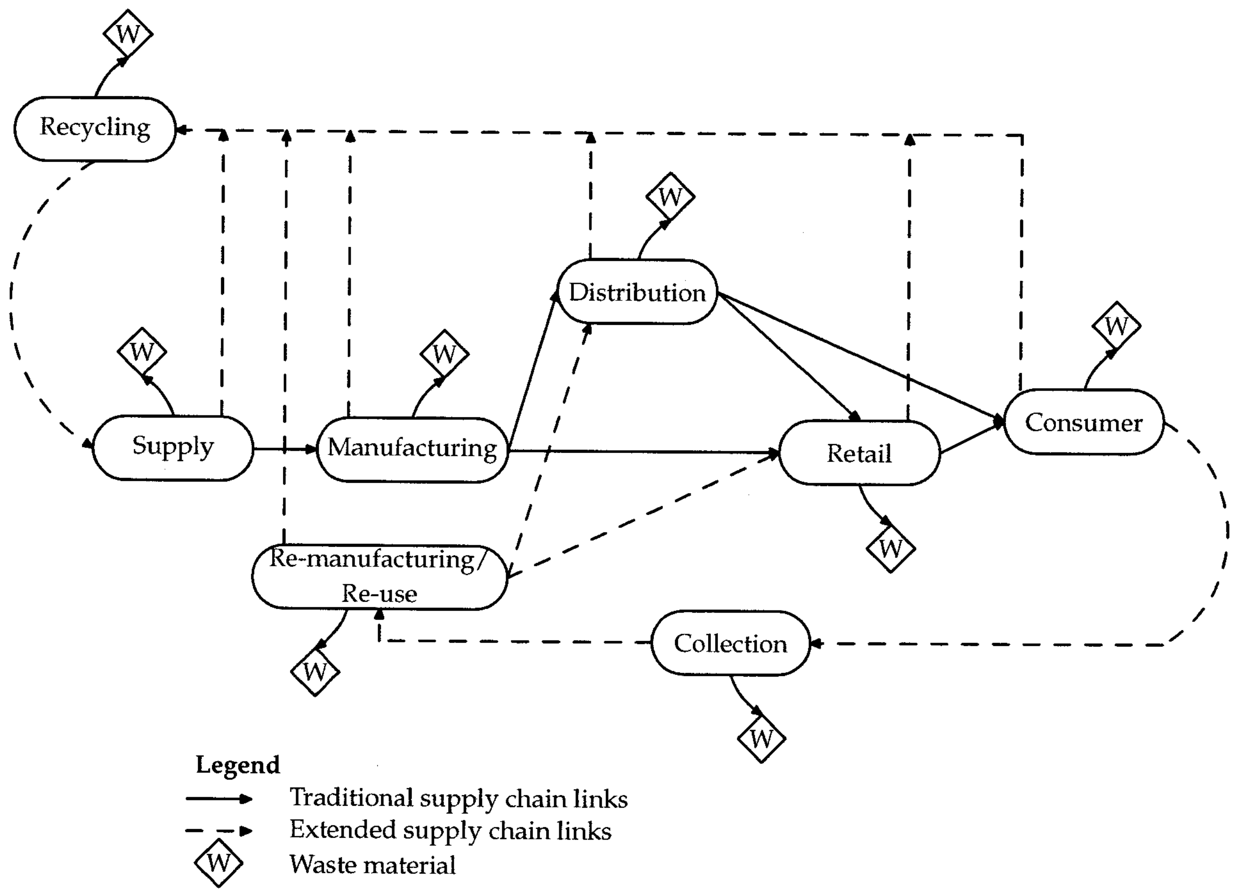

Figure 2.10: Environmental supply chain structure (from Beamon (1999))

2.3.3.5 Supply chain-level modeling for retrofit process design

When a company considers investing in large design projects, it should not only evaluate the profitability and legal environmental regulations at the process level, i.e. the plant site. An approach should be taken to also take into account the impact the design changes may have at the supply chain level using LCA and supply chain models. To our knowledge, this has yet to be considered systematically in retrofit design approaches. This approach should use process and cost information that results from an operations-driven cost model, thus using process-level information at the supply chain level. As such, this approach would first consider the process design, followed by taking into account the supply chain aspects. Furthermore, including supply chain modeling and LCA in such an approach will lead to a broader understanding of the impact of the design changes at this level.

2.3.4 Multi-Criteria Decision Making methods

2.3.4.1 Classification of methods

In engineering, decisions made on the corporate or plant level have historically been money-driven. The environmental impact of a process or product is however playing an increasingly larger role in the decision making process (Suslick & Furtado, 2001). This transforms the traditional single criterion decision making problem (based only on economic considerations) into a Multi-Criteria Decision Making (MCDM) problem, and thus a more complex situation emerges. Therefore, a thorough analysis must be carried out to make well-informed decisions that reflect the true preferences of the decision makers.

Decision analysis, defined as "a formalization of common sense for decision

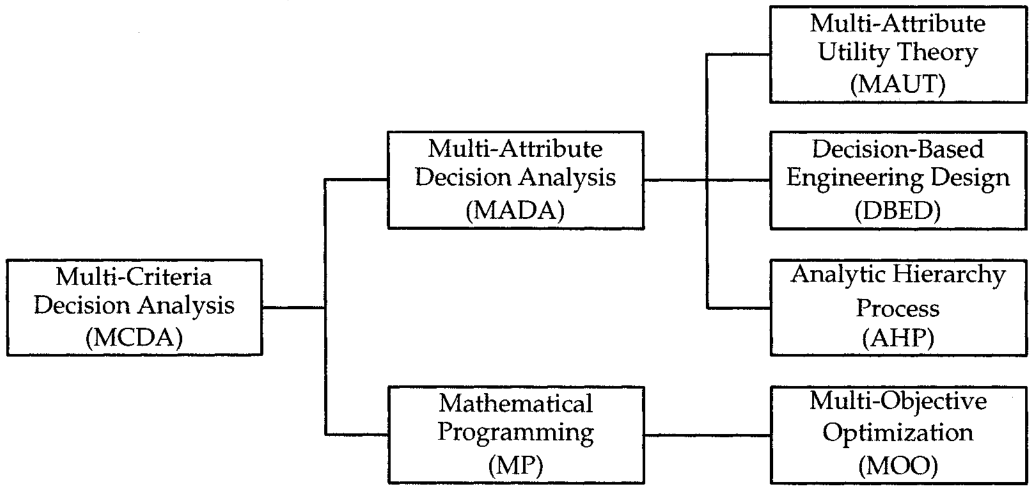

Figure 2.11: Classification of the decision-making methods reviewed

problems which are too complex for informal use of common sense" (Keeney, 1982), can be carried out using Multi-Criteria Decision Analysis (MCDA) [2]. MCDA methods can be classified into two groups: Multi-Attribute Decision Analysis (MADA) and Multi-Objective Optimization (MOO) (Figure 2.11) (Seppälä, 2003).

2.3.4.2 Multi-Objective Optimization methods

Multi-Objective Optimization (MOO) methods have been used for the optimization of existing processes and the design and synthesis of new processes. Using MOO results in finding the Pareto frontier for a given problem. The Pareto frontier is the set of non-inferior solutions for which it is impossible to improve any one objective without resulting in a detrimental effect on another. Many of these applications have focused on the trade-off between economic and environmen-

[2]MCDA is also called Multi-Criteria Decision Making or MCDM

tal objectives. For instance, MOO has been used to generate optimal waste management strategies for solvent recovery (Chakraborty & Linninger, 2002) and for the optimization of an industrial ecosystem (Singh & Lou, 2006). In particular, LCA has been recognized as a potentially powerful decision making tool for identifying Pareto-optimal design alternatives. Economic performance and LCA-based environmental objectives have been used in MOO formulations for process design and optimization (Stefanis et al., 1995; Alexander et al., 2000; Diwekar, 2003; Hugo & Pistikopoulos, 2005).

MOO is a powerful decision making tool. However, it does not lead to the choice of a single preferred design alternative. Rather, MOO generates design alternatives. This means that a trade-off, which depends on a decision maker's preferences, needs to be found between the environmental burden and the traditional economic incentives in order to determine the preferred alternative. Multi-Attribute Decision Analysis methods have been developed to accomplish this.

2.3.4.3 Multi-Attribute Decision Analysis

Multi-Attribute Decision Analysis (MADA) methods are a class of methods that deal with decision problems for which discrete design alternatives are known beforehand. MADA can be divided into four steps (Figure 2.12) (Keeney, 1982). First, the decision problem is structured by specifying the objectives, criteria and attributes, and alternatives are generated. The consequences of an alternative determine the criteria for the decision and these are characterized or quantified by attributes. Furthermore, the criteria, and consequently the attributes, need to reflect the objectives of the decision. For instance, if the decision is based on economic and environmental objectives, then the consequences of choosing an alternative needs to be measured with economic and environmental attributes. Second, the possible impact (i.e. consequences) of the alternatives is assessed. When feasible, models should be developed to determine probabilities of the consequences of the alternatives. Third, the preference of the decision makers is elicited by determining decision weights and utility functions. Finally, the alternatives are compared and evaluated, and a sensitivity analysis is carried out.

Multi-Attribute Utility Theory

One theory for describing the preferences of a decision maker is Multi-Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1976). Utilities are a measure of preference and are used when the decision maker does not exactly know the consequences of a decision that will be made. Therefore, MAUT is suitable for decision making under uncertainty. Using MAUT, two attribute characteristics need to be determined:

- The preference the decision maker has for a range of attribute levels. This is done by determining the utility function $u_i(x_i)$ for criterion i over a range of values for an attribute x_i. This can therefore be characterized as an *intra*-comparison of preference for attribute levels.
- The importance of an attribute compared to the other ones. This is done by determining the weight k_i of an attribute for criterion i. This is characterized as an *inter*-comparison of importance between attributes.

The most common formulation of the (overall) multi-attribute utility function is the additive utility function, which requires that the utilities are additively

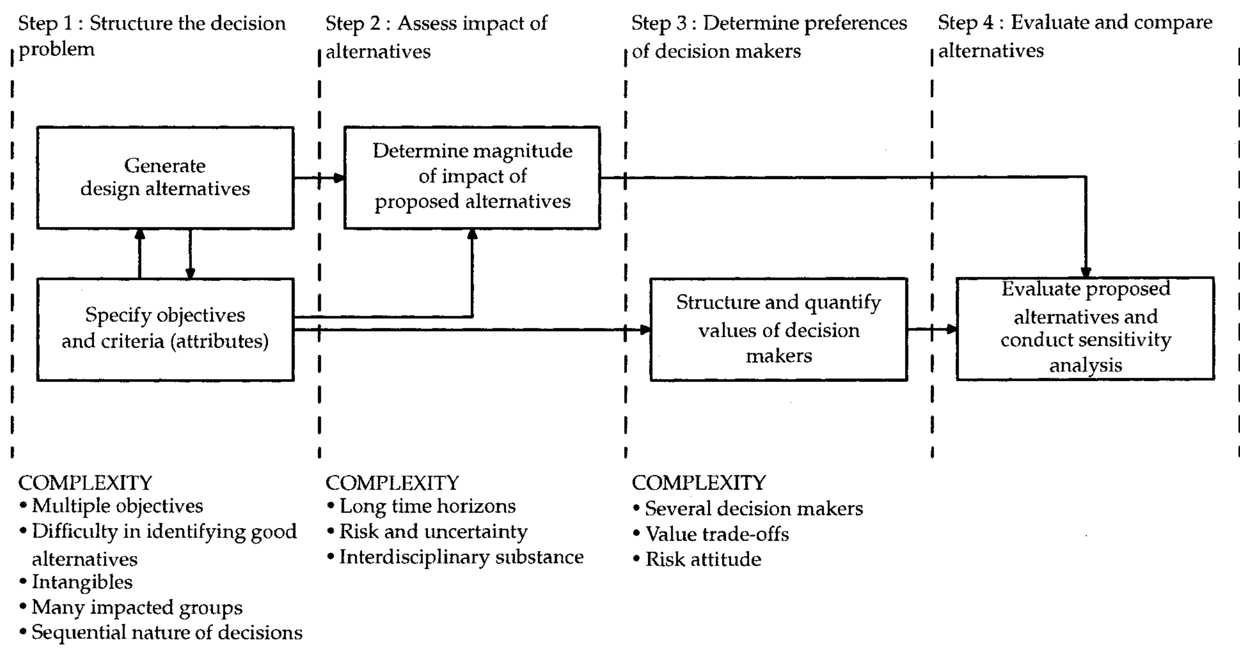

Figure 2.12: Schematic representation of the steps of decision analysis (from Keeney (1982))

independent:

$$u(x) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{2.2}$$

with: $\sum_{i=1}^{N} k_i = 1$ and $0 \leq k_i \leq 1$.

Keeney (1974) showed that if this independence does not hold, then the multiplicative form for aggregating individual utility functions must be used:

$$Ku(x) + 1 = \prod_{i=1}^{N} [Kk_i u_i(x_i) + 1] \tag{2.3}$$

where K is a scaling constant with $1 + K = \prod_{i=1}^{N}(1 + Kk_i)$ and $0 \leq k_i \leq 1$.

The individual utility functions can be chosen such that parameters in the function are a measure of the attitude towards risk of the decision maker (Figure 2.12, step 3). The attitude towards risk is invoked by the uncertainty in the decision to be made, i.e., risk is a result of uncertainty (Hazelrigg, 1999). A decision maker can be risk averse, risk prone, or risk neutral, and the value(s) of the utility function parameter(s) quantify this behaviour.

MAUT has been used for the selection of new technology for solid residuals treatment (Duarte, 2001) and for improving investment decisions in petroleum exploration (Suslick & Furtado, 2001). Both applications used a diverse set of criteria (e.g. cost, environment, public image, technological advancement) to quantify the objectives of the decision problem. However, neither used detailed models or data to characterize the consequences of the alternatives. For instance, Duarte (2001) used dimensionless attributes for environmental criteria due to the difficulty of obtaining environmental measurements.

Decision-Based Engineering Design

Decision-Based Engineering Design (DBED) is a methodology that was developed in the mechanical engineering community (Hazelrigg, 1998). DBED seeks to base engineering design decisions on information obtained from various sources, not necessarily all related to engineering. DBED is based on MAUT and is therefore capable of considering multiple objectives and characterizes uncertainty in a design. The difference with MAUT is that DBED uses the multi-attribute utility function as the objective for an optimization in order to determine the optimal design, whereas MAUT uses this function for the evaluation of several discrete design alternatives. DBED thus generates an alternative based on the preferences of the decision maker. Therefore, the method cannot be used for a design decision in which the discrete alternatives are already known beforehand. Nevertheless, DBED is a good demonstration of the applicability of MAUT in engineering design. Decision-Based Engineering Design has been applied in mechanical design problems such as material selection in the automotive industry (Thurston, 1990) and green mechanical engineering (Thurston & Srinivasan, 2003).

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a decision methodology that was developed by Thomas L. Saaty (Saaty, 1980, 1990b). AHP starts by building a decision hierarchy including the objectives, criteria and alternatives, and then uses pair-wise comparisons at all levels of this hierarchy to determine the preferred alternative according to the decision maker. This is done by calculation of the eigenvector of the pair-wise comparison matrices, which yields the decision weights for the criteria. There has been a debate between the proponents of AHP and utility theory concerning the validity of both methods (Dyer, 1990; Harker & Vargas, 1990; Saaty, 1990a). AHP has been criticized especially for its axiomatic foundations and the phenomenon of rank reversal and may therefore not reflect the true preferences of the decision maker (Dyer, 1990). It was shown that rank reversal is a mathematical consequence of the normalization procedure of AHP (Moffett, Dyer, & Sarkar, 2006). On the other hand, AHP proponents criticize the assumptions made in utility theory and the use of lotteries to elicit preferences (Saaty, 1990a).

AHP has been applied in chemical engineering problems to consider economic and environmental objectives in various problems. Eagan & Weinberg (1999) (Eagan & Weinberg, 1999) used AHP to compare two anodizing processes based on a streamlined life cycle analysis. Zhou *et al.* (2000) considered sustainability in supply chain optimization and used AHP to determine the weights for a goal programming objective function. Wen & Shonnard (2003) did an economic and environmental assessment for heat exchanger networks design and used AHP to integrate economic and environmental metrics to determine the optimal minimum approach temperature. Finally, Cornejo *et al.* (2005) used AHP to calculate a new environmental performance metric, integrating LCA and Environmental Impact Assessment (EIA) metrics, for the environmental evaluation of retrofit design alternatives. An expert panel carried out the weighting to construct this metric. The different opinions of the experts were used for a sensitivity analysis of the weights.

2.3.4.4 Comparison of MCDA methods

Table 2.3 summarizes some of the features of the MCDA methods that were reviewed. Using MOO techniques, design alternatives can be generated for which both economic and environmental considerations are taken into account. However, it is mathematically impossible to find a single optimal alternative, i.e. there is always a trade-off between the objectives. The next step in the

Table 2.3: Comparison of MCDA methods

	MOO	DBED	MAUT	AHP
Goal	Generation of alternative(s)	Generation of one alternative	Ranking of alternatives	Ranking of alternatives
Alternatives	Not known beforehand	Not known beforehand	Known beforehand	Known beforehand
Mathematical tool	Mathematical programming	Multi-attribute utility function + mathematical programming	Multi-attribute utility function	Preference matrix calculations

decision making process would be to determine which is the optimal alternative according to the decision maker's preferences. MAUT can be employed for making such a decision and has been applied in some chemical engineering problems. DBED has been developed based on MAUT, but cannot be used when discrete alternatives are evaluated. AHP is a well-established technique for tackling multi-criteria decision problems. However, the validility of AHP as a decision method has been the subject of debate since its emergence. Furthermore, preference and importance are considered separately in MAUT by using utility functions and decision weights respectively, whereas AHP considers both in a single weight. This makes MAUT a more complex, yet more transparent and rigorous decision method.

2.3.4.5 Multi-criteria decision making for retrofit process design

Traditionally, design decision making has been carried out based on economic objectives only. Currently, the environmental impact of a process starts to play an increasingly larger role in the evaluation of design alternatives and therefore both economic and environmental objectives have started to be used in the decision making process. Furthermore, the availability of process and cost data, and the use of modeling and process systems engineering tools help to compile a set of comprehensive decision metrics that characterize the design alternatives. Using MAUT in conjunction with such tools for retrofit process design has not been dealt with in the chemical engineering literature. Using an expert panel to determine the decision weights and utility functions will bring together people with different technical backgrounds which may lead to a more balanced evaluation of the decision metrics based on their values.

2.4 Process design for sustainability

2.4.1 Process systems engineering for sustainable process design

In recent years, sustainability has gained more attention in the chemical industry. The Brundtland commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987). The concept of sustainable development consists of three dimensions: an economic, an environmental and a social dimension. Traditionally, in chemical process design, only the economic dimension has been considered explicitly as an objective and the environmental and social aspects of process design have been used as constraints (Dantus & High, 1996; Ng, 2004; Smejkal, Linke, & Baerns, 2005; Uerdingen, Fischer, Gani, & Hungerbuhler, 2005). Many companies claim to have adopted sustainable business practises in order to enhance reputation, competitive advantage and cost savings. Design for sustainability is one of those business practises that can contribute to tangible financial value, intangible assets (e.g. reputation, human capital, innovation) or value for stakeholders (Bakshi & Fiksel, 2003).

Considering sustainability in process design or optimization offers many opportunities for the application of process systems engineering (PSE) (Bakshi & Fiksel, 2003). Since sustainability is a property of an entire ecosystem, and not only a property of an individual subsystem such as a production plant, the system boundaries need to be expanded outside a plant's or even a corporation's boundaries. Furthermore, considering sustainability requires that the boundaries of analysis include socio-economic-ecological aspects. Also, the quality of data from different sources needs to be ensured through reconciliation.

Another important point in the use of sustainability for design purposes is how to measure it. Sikdar (2003) discussed types of metrics for sustainability and made the distinction between the use of aggregate metrics and one-, two- and three dimensional metrics (based on the three dimensions of sustainability). The three-dimensional metrics would fully reveal the sustainability features, whereas the one- and two-dimensional metrics would help to further elaborate for decision making. The consolidation of these separate metrics in aggregate metrics, which would provide an overall measure for sustainalbility, is difficult and would need the valuation (e.g. monetization) of these metrics. This could be accomplished using multi-criteria decision analysis.

2.4.2 Applications of sustainable process design

Most applications in the chemical engineering literature have focused on the trade-off between economic and environmental performance when considering sustainability during process design. Clift (2003) stated that the social dimension presents the greatest difficulty for finding appropriate indicators to reflect social objectives. These indicators have focused on a company's own activities and not on the social value of the products or services of a company. Some approaches used LCA to expand the environmental perspective to the product level but considered economics from a plant perspective (Stefanis et al., 1995; Alexander et al., 2000; Diwekar, 2003). Hugo & Pistikopoulos (2005) included supply chain aspects in order to also expand the economic perspective from the plant level to the supply chain level. So far, the applications that consider sustainability for process design using LCA and/or supply chain modeling have been for greenfield design. There are numerous other examples in the literature that consider both economic and environmental objectives, but these did not systematically consider the complete product life cycle for design or optimization. Rather, these applications used *ad hoc* metrics that reflect the sustainability of a design (Zhou, Cheng, & Hua, 2000).

Azapagic *et al.* (2006) proposed a methodology that integrates sustainability into process design and considered the product life cycle and complete design cycle, from project initiation to final design. In this methodology, all three sustainability dimensions were represented, but were not integrated into one overall sustainability metric. This methodology also focused on greenfield process design and did not consider supply chain aspects.

2.4.3 Sustainable design in the pulp and paper industry

Cornejo *et al.* (2005) used an aggregate environmental metric, composed of the weighted sum of LCA and EIA (Environmental Impact Assessment) metrics, and the Net Present Value (NPV) to compare retrofit design alternatives during the preliminary design phase. The trade-off between the environmental metric and NPV showed that the alternative with the highest NPV had the second highest environmental performance and was considered the best candidate for further detailed design. However, the LCA that was carried out was a gate-to-gate LCA and thus considered only the environmental impact of the plant and did not include the supply chain level.

Process design for sustainability is still a largely unexplored field in the pulp and paper industry. Combining PSE tools that consider the supply chain level, i.e. LCA and supply chain models, with tools that are situated at the process level, i.e. an operations-driven cost model, will yield metrics that cover both levels. The metrics may then be used in a multi-criteria decision making panel and lead to the identification of more sustainable design alternatives due to the expansion of the system boundaries. Using these tools in a new retrofit design methodology will also ensure that process and cost data are used correctly across the system through their reconciliation in the operations-driven cost model. In this context, reconciliation refers to the synchronization of the process and cost data.

2.5 Gaps in the body of knowledge

Design methodology

There is no retrofit design methodology that uses process and cost data available from information management systems for the calculation of design decision metrics with process systems engineering tools in order to identify more sustainable retrofit design alternatives in the early design phase using multi-criteria decision analysis.

Cost modeling

There is no operations-driven cost modeling approach based on ABC-like principles for continuous processes that reconciles process and cost data and has the flexibility to include models for more advanced operations and marginal cost analysis in order to better evaluate design alternatives.

Supply chain-level modeling

To our knowledge, combining LCA and supply chain modeling for the characterization of a design alternative at the supply chain level has not been carried out for retrofit process design.

Multi-Criteria Decision analysis

There is no retrofit design methodology that employs Multi-Attribute Utility Theory which uses process- and supply chain-level decision metrics that are calculated with process systems engineering tools and weighted by an expert panel for the identification of the most preferred retrofit design.

CHAPTER 3

OVERALL METHODOLOGICAL APPROACH

Reason well from the beginning and then
there will never be any need to look back with confusion and doubt.
Tenzin Gyatso, 14^{th} Dalai Lama (1935–)

3.1 Case study: Retrofit design at an integrated newsprint mill

3.1.1 Background for the case study

Newsprint production is an energy-intensive process because it requires large amounts of steam and electricity. Steam is produced in a boiler plant by burning fossil fuel and/or biomass. Thermo-mechanical pulp (TMP) production requires large amounts of electricity due to its consumption by the TMP refiners. The refiners process wood chips to produce wood fibre and, as a by-product, low grade steam. A number of techniques have been available to reduce the electricity consumption of the refiners, but they yield only marginal gains in electrical efficiency. On the other hand, a de-inked pulp (DIP) plant uses waste paper to produce fibre, and uses much less electricity per tonne of fibre produced than a TMP plant. In this context, partly or completely replacing TMP pulp production with increased production of de-inked pulp will dramatically affect the mill-wide energy consumption. Also, due to an increase of steam production in the mill's boiler plant to compensate for the decrease or absence of steam production in the TMP plant, the increase of DIP pulp production can give rise to a potential opportunity for cogeneration. The case study in this work considers the implementation of increased de-inked pulp production and cogeneration at an integrated newsprint mill.

3.1.2 Base case mill

The base case integrated newsprint mill on which this study is based consists of the following production departments (Figure 3.1):

- 4 newsprint machines with a total average production of 1100 tonnes/day of newsprint
- 2 TMP lines with a total average production of 925 tonnes/day of pulp
- A DIP plant with a total average production of 175 tonnes/day of pulp, of which 85% of the wastepaper used is old newspaper (ONP) and 15% is old magazine paper (OMG).

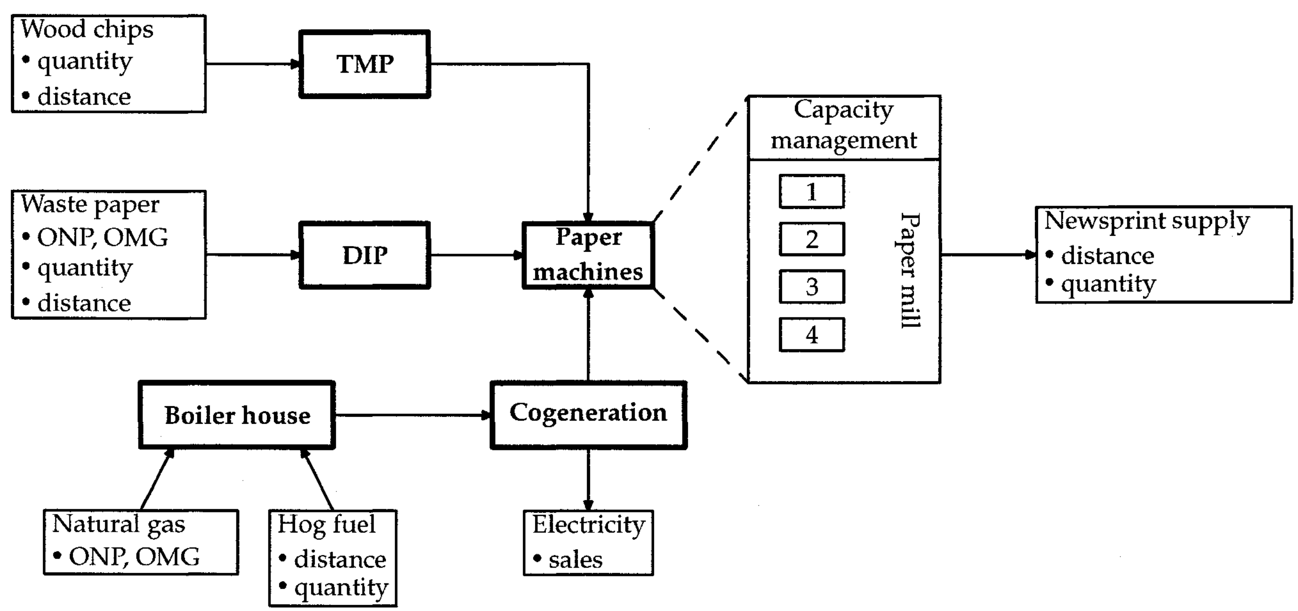

Figure 3.1: Flow diagram of the base case mill process and main inputs and outputs

In addition, the following supporting processes are part of the base case mill design:

- A wastewater treatment plant that processes 50,000 m^3/day (not shown in Figure 3.1)
- A boiler plant that produces 7,850 GJ/day of steam
- A back-pressure turbine that generates 0.4% of the total electricity demand of the mill.

3.1.3 De-inking and cogeneration configurations

The DIP plant process design configurations considered in the case study were an increase of DIP production to either 550 tonnes/day or 1100 tonnes/day (representing a 50% or 100% DIP integrated newsprint mill, respectively) (see Table 3.1). Both the 1-loop and 2-loop DIP technologies were considered. A 1-loop DIP system is a system that processes the recycled paper in one alkaline cleaning stage. A 2-loop system has an additional second cleaning loop that operates under acidic conditions making it a more rigorous cleaning process. The 1-loop de-inked plant configuration is the more typical configuration used in North America, and its capital cost is lower when compared to a 2-loop system with the same capacity. On the other hand, a 2-loop configuration provides more rigorous technology to compensate for the fact that the quality of recycled paper is expected to degrade in the future (Cody, 2003). The cogeneration configurations had the following characteristics (see Table 3.2 and Figure 3.2):

- Ability to increase biomass burning by the installation of hog fuel boilers

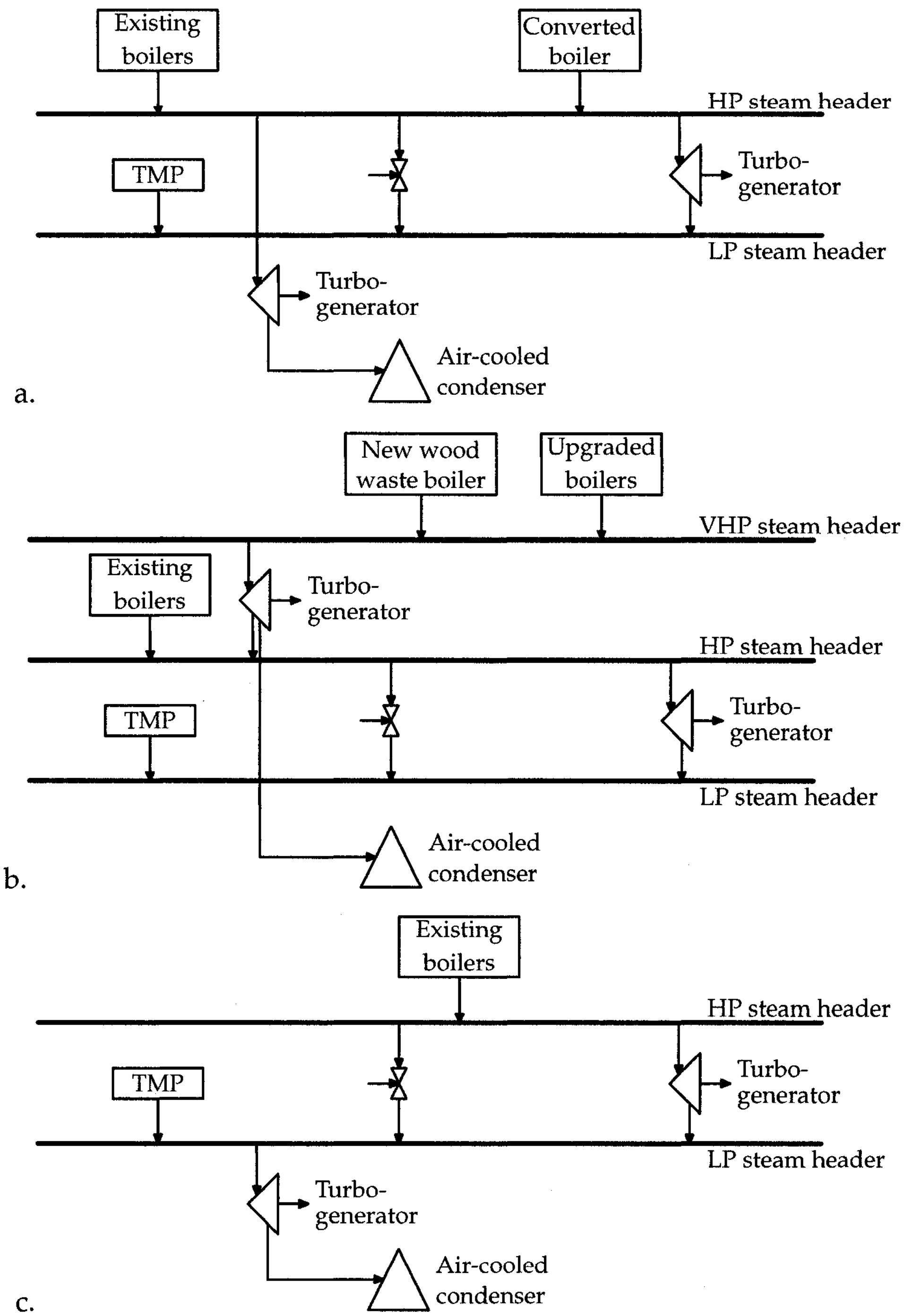

Figure 3.2: Cogeneration configurations: a. option A, b. option B, and c. option C

Table 3.1: DIP plant configurations

Option	Description
1	New 550 tonnes/day DIP plant, 1-loop
2	New 550 tonnes/day DIP plant, 2-loop
3	New 1100 tonnes/day DIP plant, 1-loop
4	New 1100 tonnes/day DIP plant, 2-loop
5	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop
6	Increase to 550 tonnes/day by adding a second line to the existing plant, 2-loop

Table 3.2: Cogeneration configurations

Option	Description
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines are kept in service
B	New wood waste boiler (at very high pressure (VHP)) is installed. Half the boilers are upgraded to VHP operation. New backpressure turbine is added to existing ones
C	New air-cooled condenser and condensing turbine are installed

- Reactivation of equipment that is currently idle (i.e., turbines to increase electrical output) and implementation of new back-pressure turbines or condensing turbines.

In total, 18 alternatives were analyzed in this case study by considering all possible combinations of the DIP and cogeneration configurations. The following naming convention for the design alternatives was used: Alternative {DIP configuration 1 to 6 as per Table 3.1}-{Cogeneration configuration A, B, or C as per Table 3.2}.

3.2 Overall methodology

The increased production of DIP pulp and implementation of cogeneration will have economic and environmental consequences. In this work, a novel retrofit

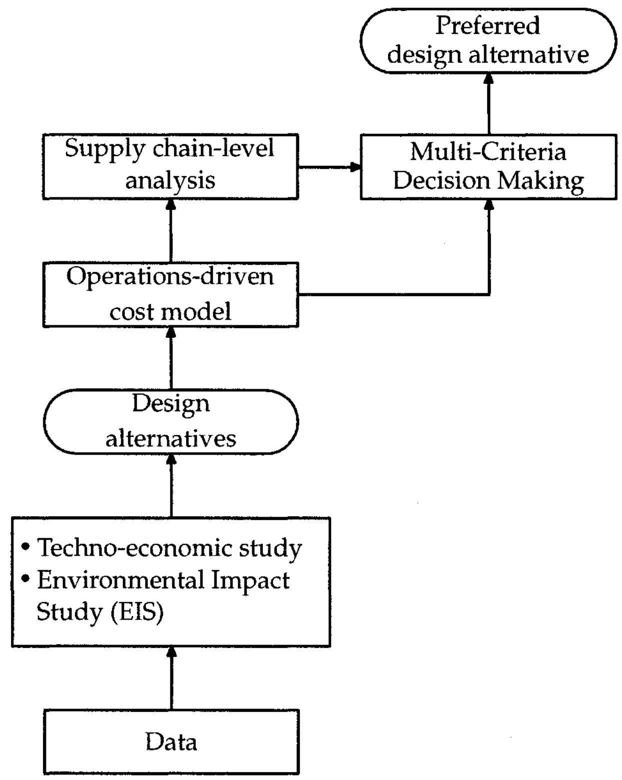

Figure 3.3: Overall methodology of the new retrofit design approach

design decision making methodology is elaborated to quantify these consequences with economic and environmental criteria using available process and cost data and process systems engineering tools. Subsequently, these criteria were used for design decision making. This methodology consisted of the following 3 parts (Figure 3.3):

1. Characterization of the retrofit design alternatives at the process level
   First, a techno-economic study was carried out in order to generate the retrofit design alternatives and to do a conventional techno-economic analysis of these alternatives. The manufacturing costs were then modeled for each alternative using a novel operations-driven cost modeling approach

that was based on:

- Process design characterization using mass and energy balances
- Activity Based Costing-like (ABC-like) accounting principles.

Furthermore, the operations-driven cost modeling approach was compared with the conventional techno-economic analysis. Using profitability metrics, a set of design alternatives was retained. The retained design alternatives were then analyzed in more detail by carrying out marginal cost analyses and cost analysis of operating variants. The cost model was implemented using Impact:EDC™ by 3C Software (http://www.3csoftware.com), a software company that has several customers in the pulp and paper industry.

2. Deduction of the consequences of implementing the retained design alternatives at the supply chain level (supply chain-level analysis)
   This analysis was carried out using:

   - A supply chain model that was developed in order to consider the impact of changing market conditions on the mill and supply chain operations using scenario analysis. This model was implemented in MS Excel using the Solver add-in (Fylstra, Lasdon, Watson, & Waren, 1998)
   - A Life Cycle Assessment (LCA) model that was developed in order to determine the environmental impact under those same market conditions at the supply chain level. The LCA model was implemented using the SimaPro software by PRé Consultants (http://www.pre.nl).

3. Determination of the preferred design alternative based on economic and environmental criteria by carrying out a Multi-Criteria Decision Making

(MCDM) panel.

This was done by using metrics that resulted from the preceding analyses. These metrics were used as measures (attributes) for the selected criteria that characterized the differences in the alternatives from an economic and environmental perspective.

CHAPTER 4

PUBLICATION EXECUTIVE SUMMARY

Our aim as scientists is objective truth;
more truth, more interesting truth, more intelligible truth.
We cannot reasonably aim at certainty.
Karl Popper (1902–1994)

4.1 Presentation of publications

The following papers, that were submitted to and/or published in scientific journals, are included in Appendix A of this thesis :

- Janssen, M., Cornejo, F., Riemer, K., Lavallée, H.-C., & Stuart, P. (2006). Techno-economic considerations for DIP production increase and implementation of cogeneration at an integrated newsprint mill. Pulp & Paper

Canada, 107(9), 33–37

- Janssen, M., Naliwajka, P., & Stuart, P. (2007). Development of an operations-driven cost model for continuous processes – Part II: Retrofit process design application. Received by TAPPI Journal on August 2nd, 2007

- Janssen, M., Gaudreault, C., Laflamme-Mayer, M., & Stuart, P. (2007). Supply chain level aspects of a methodology for sustainable retrofit process design. Received by Journal of Cleaner Production on August 2nd, 2007

- Janssen, M., & Stuart, P. (2007). Multi-criteria decision making for retrofit process design using process- and supply chain-level criteria. Received by Computers and Chemical Engineering on August 2nd, 2007

- Janssen, M., & Stuart, P. (2007). Retrofit process design methodology for sustainability. Received by AIChE Journal on August 2nd, 2007

Furthermore, the following papers, complementary with the research work done, can be found in Appendix B :

- Janssen, M., Laflamme-Mayer, M., & Stuart, P. (2003). Survey of data management systems used in the pulp and paper industry. In Focapo 2003: Proceedings Foundations Of Computer Aided Process Operations (pp. 551–554)

- Janssen, M., Laflamme-Mayer, M., Zeinou, M.-H., & Stuart, P. (2004). Survey indicates mills' need to exploit IT systems with new business model. Pulp and Paper, 78(6), 46–51

- Janssen, M. & Stuart, P.R. (2004). Business model framework for using real-time process data for design decision making. In Proceedings of the Inaugural CDEN Design Conference, comm. 07B5

- Laflamme-Mayer, M., Janssen, M., & Stuart, P. (2007). Development of an operations-driven cost model for continuous processes – Part I: Framework for design and operations decision making. Received by TAPPI Journal on August 2nd, 2007

- Janssen, M., Riemer, K., & Stuart, P. (2007). Potential cost benefits of electricity load shifting when designing upgrades to an integrated newsprint mill. Received by Paptac on July 24th, 2007

4.2 Links between publications

The papers in Appendices B.1 and B.2 discuss the results of two surveys that were carried out to explore the use of data at pulp and paper mills, and the data and information management systems that are used in the pulp and paper industry. The results of these surveys showed that the data that have become available at mills are far from being fully exploited. More specifically, it was found that tools using data for improved decision making and advanced planning and scheduling require the attention of mills.

The construction of the framework for retrofit design decision making that is elaborated in this thesis was inspired by these survey results, and introduced in the peer-reviewed conference paper entitled "Business model framework for using real-time process data for design decision making" (Appendix B.3). This position paper was presented at the Inaugural CDEN (Canadian Design Engineering Network) Design Conference in Montréal. The structure of the overall framework employed in this Ph.D was elaborated, and its constituents discussed in some detail. The framework couples process systems engineering tools with process expertise to extract knowledge from the data for decision making in a retrofit design context. Furthermore, the case study used to demonstrate the benefits and advantages of this framework is introduced. The case study considers the simultaneous implementation of increased deinked pulp production and cogeneration at an existing integrated newsprint mill. Actual mill process and cost data have been used for the case study in this work, as well as actual process constraints and practical considerations.

This case study was explored using a classical techno-economic approach reported in the paper in Appendix A.1. This study was carried out to generate the retrofit design alternatives and to obtain a benchmark with which the new framework for design decision making could be compared. The study employed "large-block analysis" which involves a systematic search for possible process design alternatives. It is based on the representation of different process systems by their overall mass and energy balances. The profitability of the resulting design alternatives was determined. Furthermore, a risk analysis revealed valuable information for decision making by including uncertainty in the analysis.

The next five papers (Appendices A.2 to A.4, B.4 and B.5) describe the implementation and use of the retrofit design decision methodology using the mill-inspired case study. The operations-driven cost modeling approach is presented in the paper in Appendix B.4. This approach aims at developing a versatile tool for representing and understanding the costs of complex continuous production environments. The paper describes the components of a novel advanced operations-driven cost model, how process and cost information can be integrated, and the process-based aggregation of costs using Activity Based Costing-like (ABC-like) principles for relating these costs to the process. The paper included in Appendix A.2 uses the operations-driven cost model to evaluate the design alternatives and operating variants. The incremental and process-wide economics of energy efficiency and production capacity change were investigated. A comparison was made with the results from the classical techno-economic study (Appendix A.1) to point out the advantages and benefits of the operations-driven cost modeling approach. In a separate paper (Appendix B.5), the cost benefits of an advanced process concept termed electricity load shifting in the TMP plant were specifically investigated using the operations-driven cost model. Load shifting consists of scheduling electricity load in such a way that electricity use is diverted from on-peak to off-peak electricity price periods. It was found that the implementation of load shifting significantly improves profitability and mitigates extreme electricity prices for the alternatives where the TMP plant was not shut down.

Next, the supply chain-level analysis was carried out as described in Appendix A.3. This analysis was carried out for the most profitable case study design alternatives using Life Cycle Assessment (LCA) and supply chain models for product-level environmental and economic perspectives. It was found that the most profitable retrofit design is not necessarily the alternative with the best performance from a supply chain perspective.

The last of the five papers deals with Multi-Criteria Decision Making (MCDM) for retrofit design. This paper, which can be found in Appendix A.4, describes the results of an MCDM panel designed to choose the preferred design alternative based on process- and supply chain-level decision criteria. Multi-Attribute Utility Theory (MAUT) was used as the decision method. The panel members weighed the outcomes for a range of criteria using the trade-off method. Furthermore, the variation in the panel member weights was used in a Monte Carlo simulation for further analysis. The results of the panel indicated that the inclusion of the process- and supply chain-level decision criteria, in addition to the classical economic profitability criteria, can alter the final decision when compared only to the classical techno-economic study.

Finally, the last paper, included in Appendix A.5, provides a synthesis of the work discussed in the previous five papers so that the overall contribution of the body of work is assembled for the chemical engineering community. It describes and discusses the design method: extracting process and cost data, using these data to create knowledge via the models developed at the process and supply chain levels, and then using this knowledge for better design decision making.

4.3 Synthesis

The goal of this synthesis is to give an overview of the most pertinent results of the work done for this Ph.D. The overall methodology was proposed at the outset of the project, and then systematically addressed as summarized below. Costs are in Canadian dollars unless otherwise stated.

4.3.1 Implementation and results of the operations-driven cost model

The goal of the initial work conducted was to develop retrofit process design alternatives based on realistic considerations from the case study mill. The operations-driven cost model was then developed to explore the impact of important modifications implicating complex process engineering and incremental cost changes.

The operations-driven cost modeling approach consisted of 4 steps (Figure 4.1) and was implemented using the Impact:EDC™ software:

① Calculation of total capital costs for each design alternative relative to the implementation of increased DIP production and cogeneration at an existing integrated newsprint mill

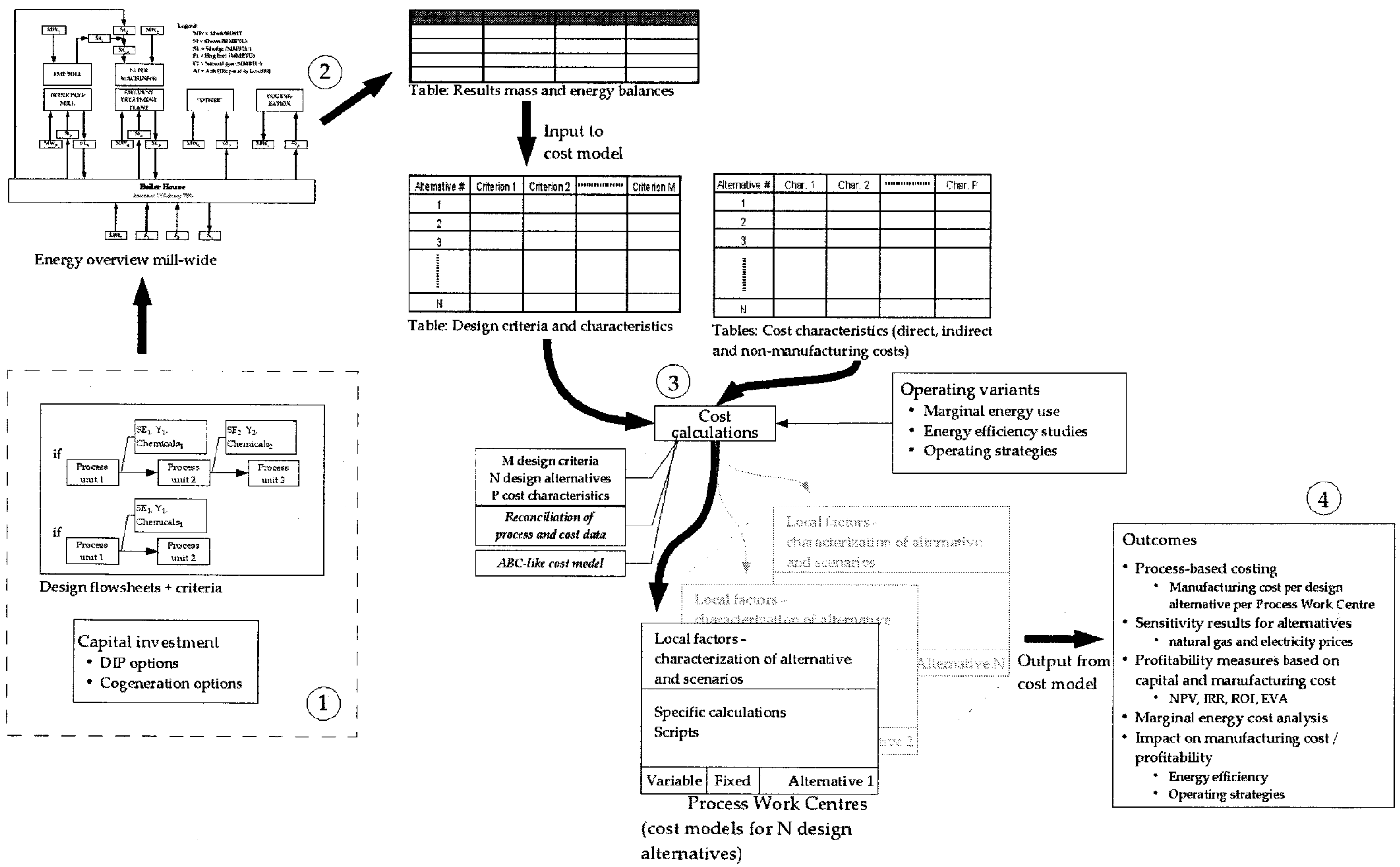

Figure 4.1: Implementation of the operations-driven cost modeling approach for retrofit process design:① capital cost calculation,② mass and energy balances,③ cost model,④ design evaluation

② Calculation of mass and energy balances for each design alternative

③ Modeling and calculation of manufacturing costs for the design alternatives and operating variants that consist of steam production changes, increased process energy efficiency and electricity load shifting

④ Calculations for the evaluation of the design alternatives and operating variants.

A thorough capital and operating cost estimate study was completed using classical feasibility engineering methodology and through close collaboration with the mill and technology suppliers. DIP options 5 and 6 (see Table 3.1) had the lowest capital cost of all DIP options, since the base case DIP plant (see section 3.1.2) was complemented with an extra capacity of 375 tonnes/day, whereas the other DIP options comprised of complete replacement of the existing DIP plant with new plants of either 550 or 1,100 tonnes/day. Cogeneration option B (see Table 3.2) was the highest capital cost cogeneration option, because it required the greatest modifications to existing equipment as well as the implementation of new equipment. The capital cost for option C was relatively low, since the only new equipment required included an air-cooled condenser and condensing turbine. It was assumed that no capital cost changes to the effluent treatment plant were required under any of the new alternatives. The total capital cost estimate for each of the design alternatives was obtained by addition of the estimates for the DIP and the cogeneration options (Figure 4.2).

The operations-driven cost model was developed with the necessary detail to extract complex cost information on process changes, as well as taking into account the available data. The model was used to calculate the manufacturing cost per tonne of the cost object (newsprint). Process and Overhead Work Centres (*PWC* and *OWC* respectively) were defined to represent the production de-

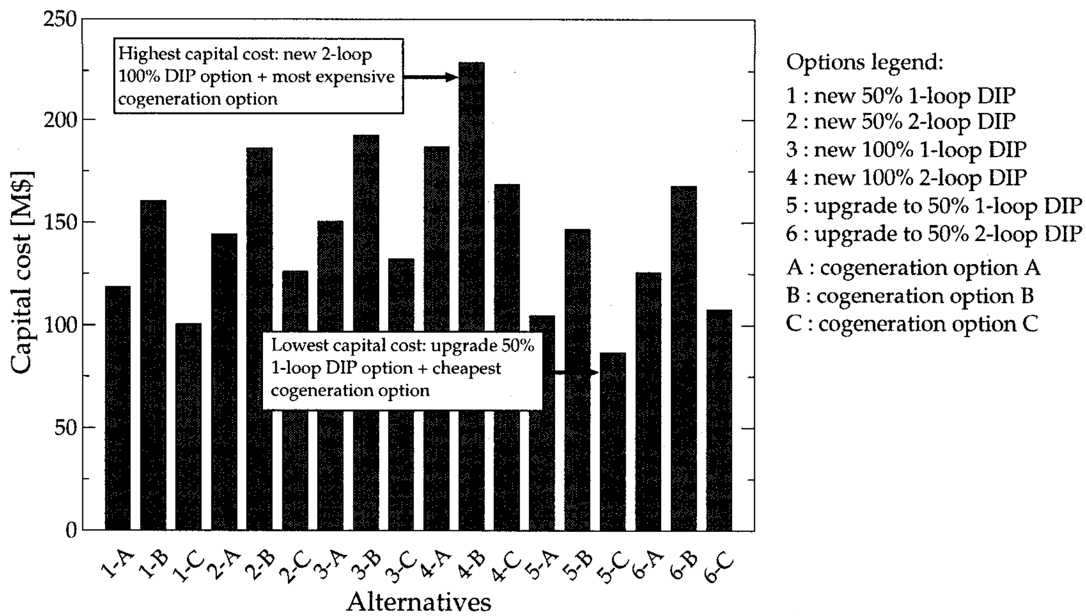

Figure 4.2: Capital costs for each design alternative based on addition of the estimates for the DIP and the cogeneration options

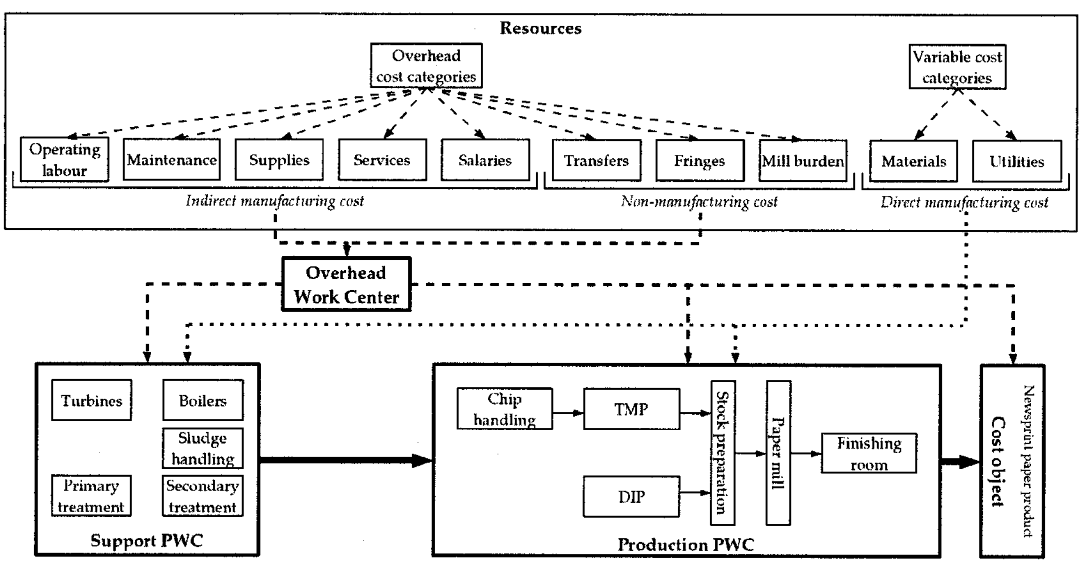

Figure 4.3: Cost categories for the case study mill and definition of the Process and Overhead Work Centres (*PWC* and *OWC*)

partments of the mill and the resources were linked to them (Figure 4.3). The *PWCs* accommodated the following elements:

- The cost and mass flow along the process
- The design criteria and characteristics of each alternative and their operating variants
- Calculations specific to each *PWC*
- The assignment of overhead costs, and finally
- The operations-driven cost calculation that was based on ABC-like principles (see also Figure 4.1).

The direct and overhead manufacturing costs were calculated per *PWC* for each alternative (Figure 4.4). The overhead costs per *PWC* were calculated in the *OWC* using allocation base information. A negative value for a *PWC* cost indicates that this work centre either had a net positive income or transferred costs to outside the paper mill. It has been assumed that cogenerated electricity can be sold to the grid with a 50% premium over the nominal electricity price, making the Turbines *PWC* an important profit centre for the alternatives. The cost of fibre was the most significant cost for the TMP and DIP plants, and varied with changes in furnish to the paper machines, i.e. whether the percentage of DIP pulp in the furnish was 50% or 100%. The yield difference between the 1-loop and the 2-loop DIP configurations (92% and 85% respectively) created a difference in fibre costs. Furthermore, there was a difference in steam consumption: the 1-loop configuration used 1.21 GJ/tonne and the 2-loop configuration, 2.18 GJ/tonne of waste paper consumed. The cost variation for the paper mill department can be explained primarily by the variation in steam price for each

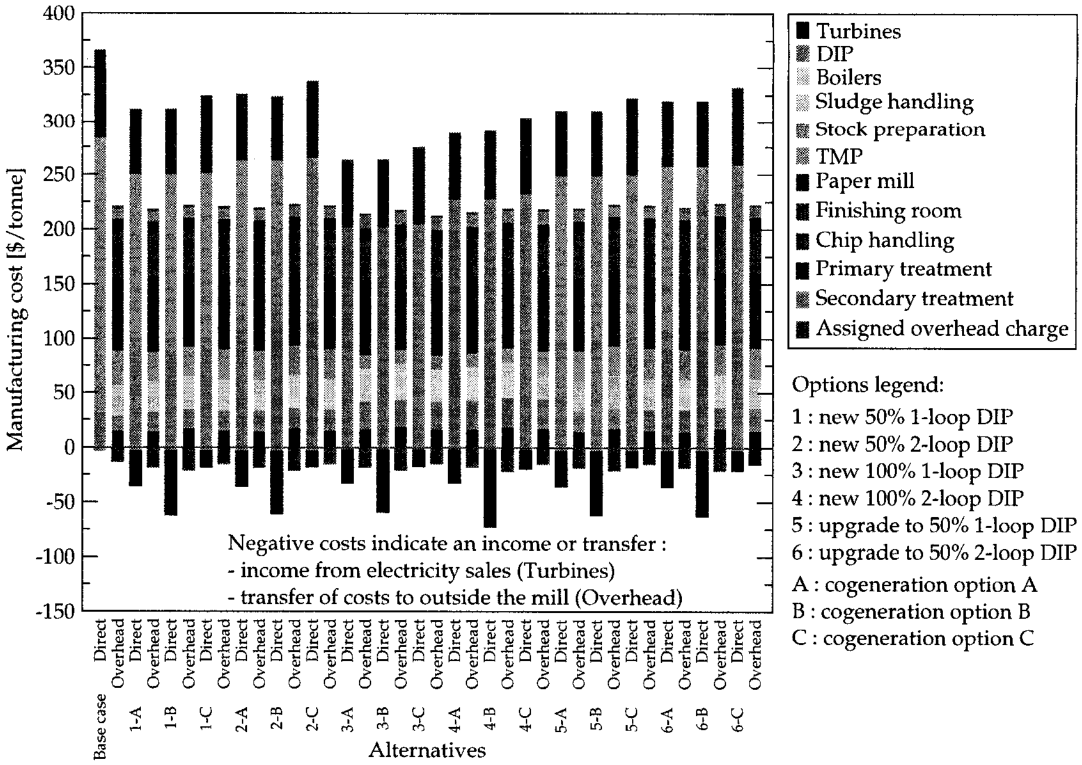

Figure 4.4: Manufacturing costs of the design alternatives split by Process Work Centre and by direct and overhead costs

design alternative, since the paper mill was the biggest consumer of steam. The steam price depended on the fuel mix that was used by each alternative. This fuel mix consisted of wood waste, natural gas, sludge produced in the DIP plant and sludge from the wastewater treatment plant. The base case mill and the alternatives using cogeneration option C had lower wood waste capacities in their boiler plants and therefore used more natural gas, resulting in a higher steam price. The increased costs due to higher natural gas use were assigned to the PWCs that used this steam because of the operations-driven nature of the cost model. The cost model thus linked the resources used and their costs to the activities in each PWC, in this case steam use, and brought process and business knowledge closer together.

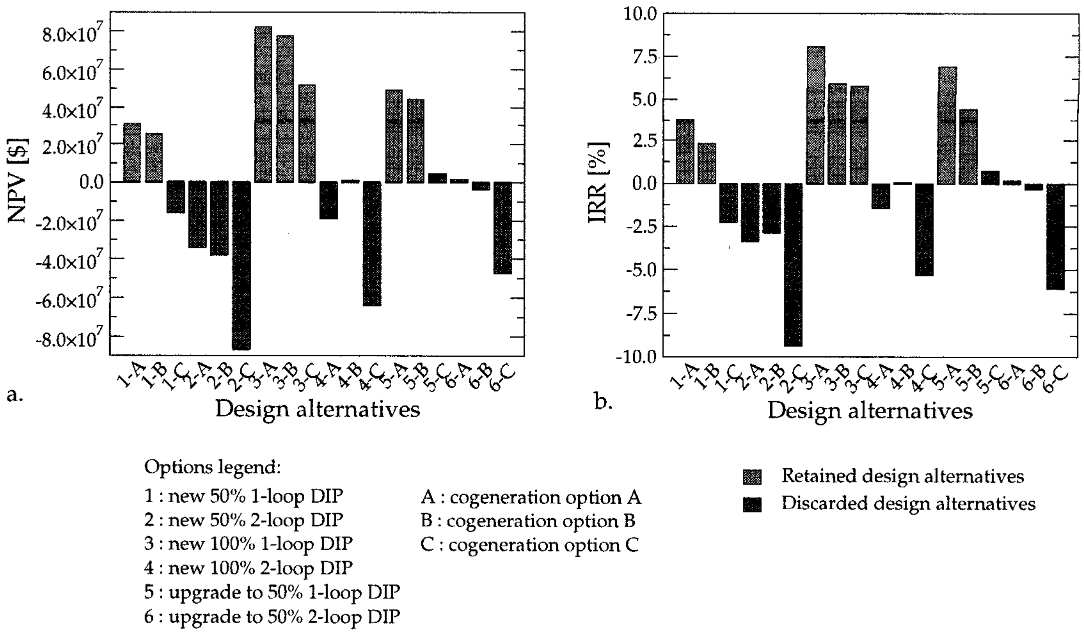

Figure 4.5: Profitability of the design alternatives: a. NPV; b. IRR

This portion of the study demonstrated that the proposed ABC-like cost model is capable of synchronizing process and cost data in order to increase the visibility and transparency of the manufacturing costs. It is also capable of relating resource use to the activities that take place in each *PWC*.

The profitability analysis revealed that ten alternatives should be retained using Internal Rate of Return (IRR) greater than 0% as the screening criterion, including the three 100% 1-loop DIP design alternatives (Figure 4.5). Three of these alternatives were discarded because they had only marginal profitabilities leaving seven alternatives for further analysis. Alternative 3-A was most profitable with an IRR of 8.1% (and an NPV of $82.3 million). Sensitivity analysis revealed that higher electricity and natural gas prices increased the profitability of the alternatives. Both natural gas and electricity consumption levels were lower in the design alternatives than in the base case mill, and therefore higher prices for

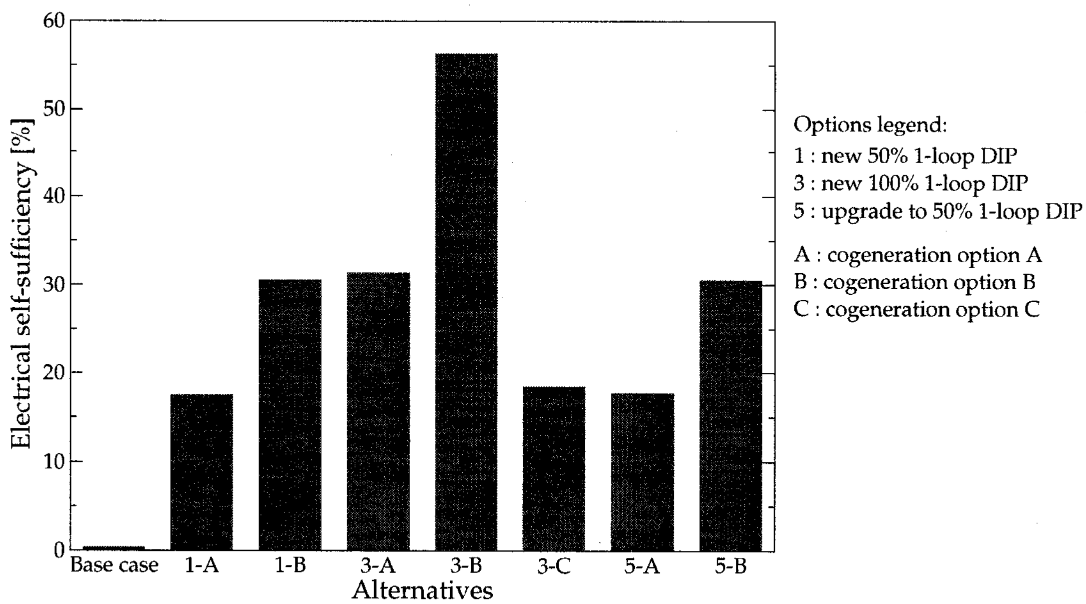

Figure 4.6: Electrical self-sufficiency of the retained design alternatives and the base case mill

both had a positive impact on the profitability of the design alternatives.

Electrical self-sufficiency, defined as the percentage of the mill electricity demand that is fulfilled by the cogenerated electricity, was calculated based on the mass and energy balances (Figure 4.6). This result was later used during the decision making panel as a measure of the energy economics of a given alternative (see section 4.3.3). The replacement of the existing DIP plant by a completely new plant or the implementation of a second new DIP line next to the existing one affected electrical self-sufficiency only minimally. The cogeneration potential of alternatives 3-A and 3-B (both 100% 1-loop DIP alternatives) nearly doubled when compared to their 50% DIP 1-loop counterparts (alternatives 1-A, 1-B, 5-A and 5-B). This was due to a decrease in the electricity demand for the 100% DIP alternatives because the TMP plant was shut down.

Marginal energy cost analysis was carried out using the operations-driven cost model for the plant in order to demonstrate the importance of considering incremental energy use in the analysis of design alternatives. The marginal steam cost, $C^{marg,steam}$, and marginal cost of generated power, $C^{marg,power}$, were calculated using the following equations:

$$C^{marg,steam} = \frac{C_q^{steam,tot} - C_{q-1}^{steam,tot}}{P_q^{steam,tot} - P_{q-1}^{steam,tot}} \tag{4.1}$$

$$C^{marg,power} = \frac{C_q^{steam,TB} - C_{q-1}^{steam,TB}}{P_q^{power} - P_{q-1}^{power}} \tag{4.2}$$

and:

$$C_q^{steam,tot} = P_q^{steam,tot} p_q^{steam} \tag{4.3}$$

$$C_q^{steam,TB} = U_q^{steam,TB} p_q^{steam} \tag{4.4}$$

where $C^{steam,tot}$ and $C^{steam,TB}$ are total steam cost [$] and turbine steam cost [$], $P^{steam,tot}$ and $U^{steam,TB}$ are total steam produced by the boiler plant [GJ] and turbine steam usage for cogeneration [GJ], P^{power} the electricity generated by the turbines [MWh], and p^{steam} is the average steam price (cost) [$/GJ]. Electricity and steam use in the paper machines were a function of the newsprint production rate, whereas the yield of the boiler plant was a function of the steam production rate.

The marginal steam cost analysis demonstrates the impact of changing the fuel mix for increased steam production (Figure 4.7a). For the alternatives with cogeneration options A and B, the marginal steam cost was lower than the average steam cost when increased steam production resulted from increased wood waste use only. After natural gas was added to the fuel mix, the marginal steam cost was higher than the average steam cost. This meant that the mill should not produce incremental steam using natural gas unless necessary. Only alternative 3-C did not display a jump in the marginal steam cost. Cogeneration option

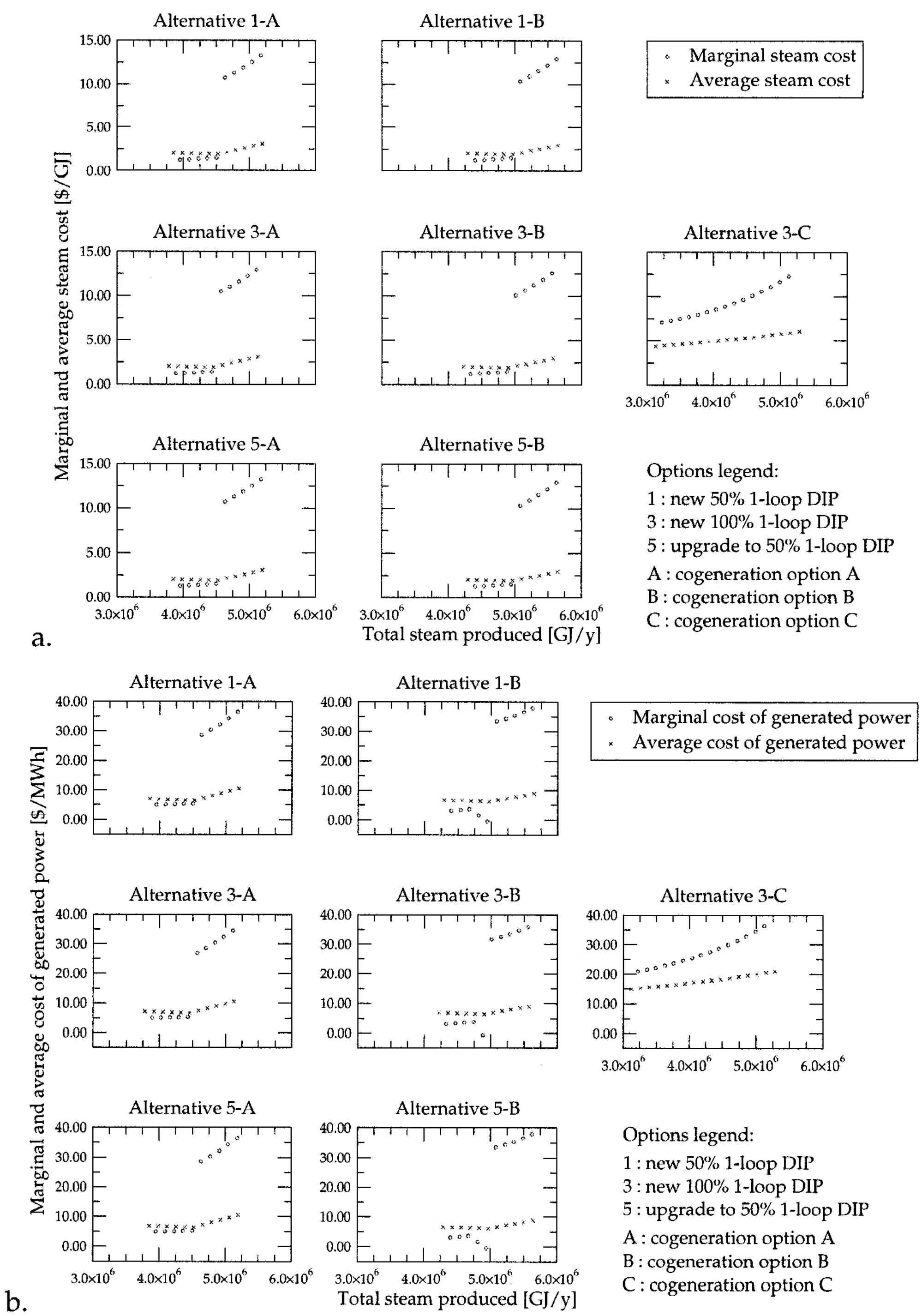

Figure 4.7: Marginal cost analysis of the retained design alternatives: a. marginal and average steam cost, b. marginal and average cost of generated power

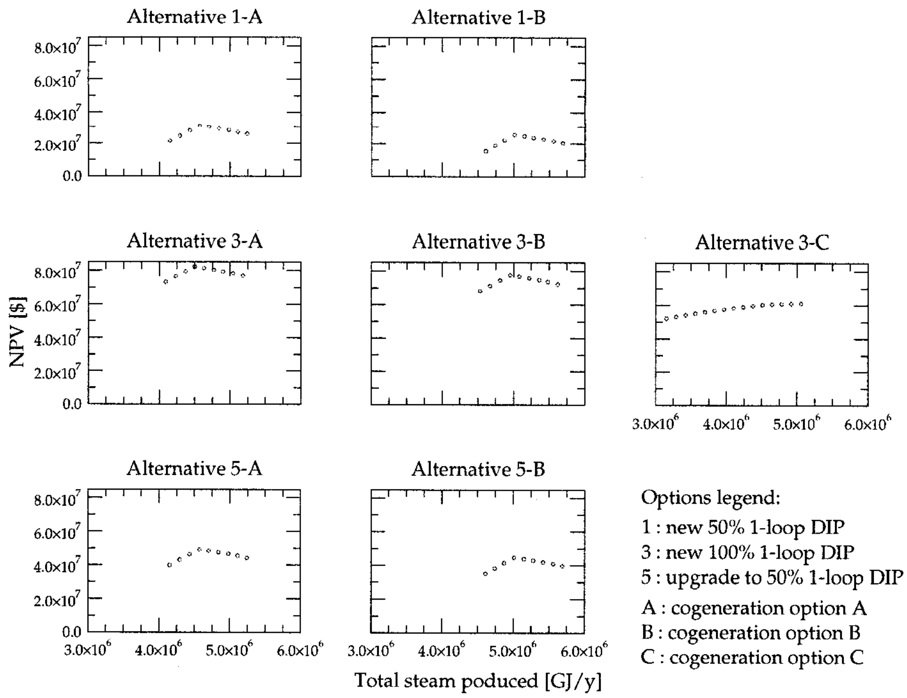

Figure 4.8: Profitability change of the retained design alternatives with varying steam production

C had a lower wood waste incineration capacity than the other cogeneration options. Therefore, natural gas was already the marginal fuel at the minimum steam production rate that satisfied the demand for this alternative. This resulted in a marginal steam cost higher than the average steam cost at all steam production rates. The average and marginal costs of generated power showed a similar trend as the average and marginal steam cost for all alternatives because of their dependence on the steam price (Figure 4.7b).

The profitability of the retained design alternatives changed when steam production was varied in the boiler plant (Figure 4.8). For the alternatives with cogeneration options A and B, optimal profitability was reached when wood waste use was maximized and natural gas use minimized. These were the operating conditions under which the initial profitability analysis was done (Figure

4.5). Alternative 3-C reached maximum profitability at a steam production of approximately $5.0 \cdot 10^6$ GJ/y while the original design produced $3.2 \cdot 10^6$ GJ/y. Although this alternative would lose more money by using more natural gas to produce excess steam (Figure 4.7a), the income of selling more cogenerated electricity would be beneficial until an optimum is reached.
The marginal cost analyses could be implemented in the cost model because the model focuses on activities that take place in the process units (or *PWCs*), e.g. steam production in the boiler plant. Consequently, changes in these activities lead to changes in resource use which leads to changes in the manufacturing costs. These marginal cost analyses give decision makers quantitative information about the operating conditions under which a design alternative would gain or lose money, and thus reach its optimal profitability. Depending on market conditions (e.g. varying fuel prices) and design specifications (e.g. wood waste capacity and/or efficiency of the boiler plant), this profitability would be reached under different operating conditions (e.g. different steam production levels). Using a classical techno-economic approach, such information would be more difficult to extract due to the fact that resource costs are then directly linked to the product instead of to the activities that take place in a process unit (*PWC*).

Many mills are currently seeking to decrease energy usage by incremental process changes, in order to decrease reliance on fossil fuels and their increasing cost. Increasing the process energy efficiency of the design alternatives affected the profitability of the design alternatives according to Figure 4.9. When the steam production in the boilers was decreased by the same quantity as was conserved by the higher energy efficiency, profitability decreased significantly due to lower electricity generation. On the other hand, when the steam production in the boilers did not change, the profitability increased with increasing energy

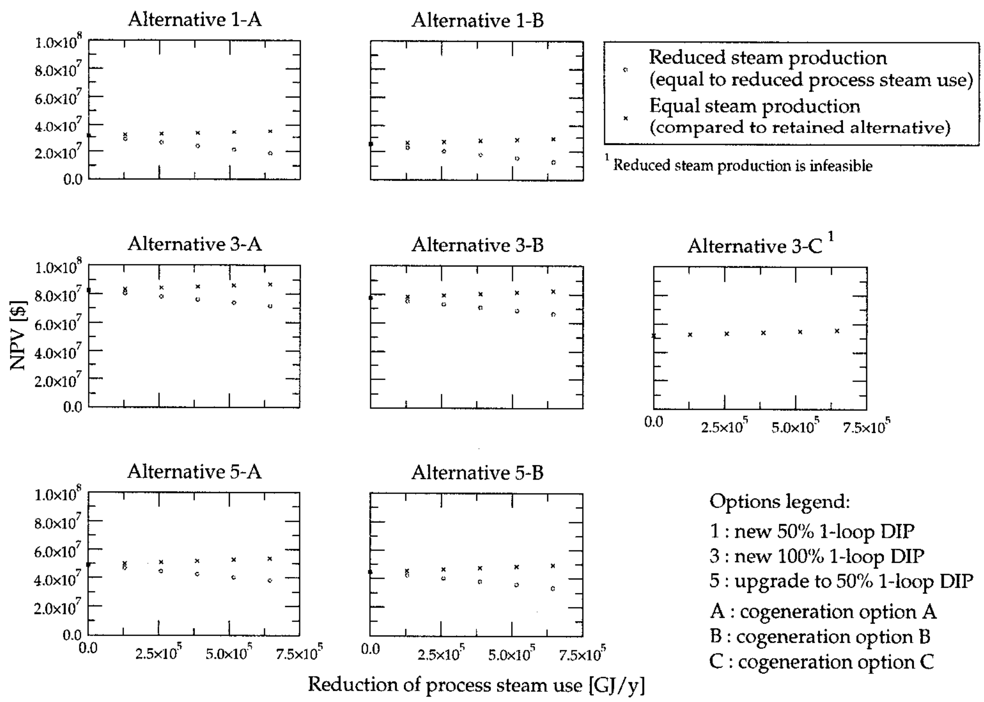

Figure 4.9: Impact of energy efficiency on the profitability of the retained design alternatives

efficiency. Therefore, a maximum of excess steam for electricity generation, i.e. steam production exceeding process steam demand, should be available while maintaining an optimal fuel mix in order to optimize profitability.

Electricity load shifting is the scheduling of the electricity load in such a way that electricity use is diverted from on-peak to off-peak electricity price periods (Ashok & Banerjee, 2000). This is particularly of interest for a TMP plant. Load shifting is increasingly more common due to increased electricity prices, but cannot be easily incorporated systematically into design decision making. The operations-driven cost model was applied in order to quantify the advantages of using electricity load shifting as an operational strategy. This was done by modeling the electricity usage in the TMP plant inside the TMP *PWC*. Table 4.1 gives an illustration of the changes in the mill-wide energy profile of a

Table 4.1: Impact of electricity load shifting on the mill-wide energy profile of a 50% DIP design alternative

Operating conditions [a]	Steam production boiler plant	Electricity generation [b]	TMP pulp production	Boiler steam use [c]	Total electricity use [d]
No load shifting [e,f]	100	100	100	100	100
Load shifting [g,h]					
a. TMP plant shutdown	100	90	0	110	50
b. TMP plant running	100	110	200	90	150

[a]The ratio of produced DIP and TMP pulp is 50:50
[b]May vary with cogeneration configuration
[c]Boiler plant-produced steam used in the process
[d]Electricity use for the whole mill
[e]All set to 100 to serve as a benchmark
[f]Without load shifting; only one TMP line is in operation
[g]With load shifting; the TMP plant is shut down 50% of the time
[h]There are 2 separate TMP production lines

50% DIP alternative when an electricity load shifting strategy is implemented. When the TMP plant is shut down, there is no TMP steam production and the boiler steam use (i.e. use of steam produced by the boiler plant) in the process increases. Consequently, there is less steam available for the turbines for electricity generation. When the TMP plant runs at maximum capacity, boiler steam use decreases. This results in an increase of potential electricity generation because more steam that is produced by the boiler plant is available to the turbines. However, the profit that can be made by not producing TMP pulp during peak electricity price hours is more attractive. This is especially true if a real-time (or similar) pricing strategy is used (Roos & Lane, 1998).

Applying an electricity load shifting strategy with set on-peak and off-peak electricity prices had a significant impact on the profitability of the 50% DIP alternatives (Figure 4.10): three more design alternatives became profitable. Alternative 3-A remained the most profitable, but in particular alternatives 5-A and 5-B

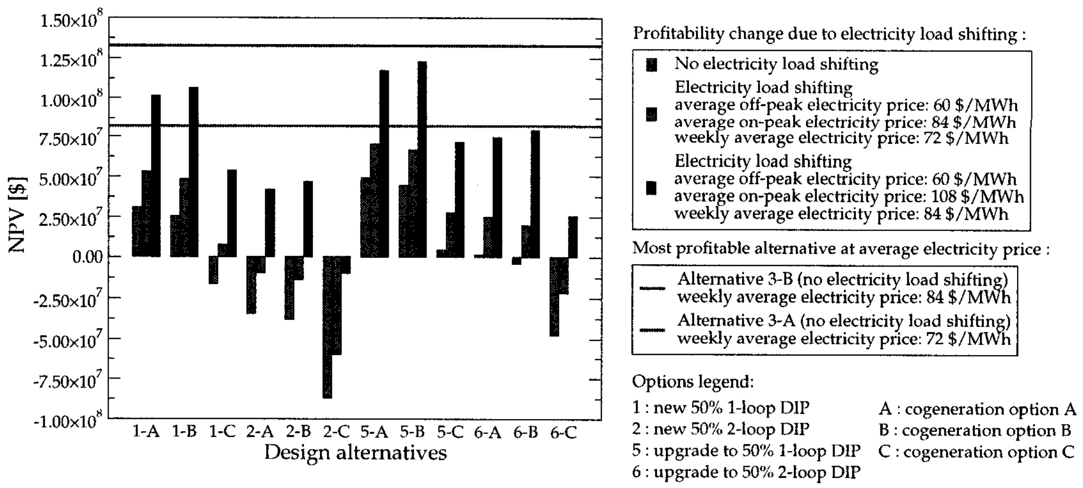

Figure 4.10: Impact of electricity load shifting on the profitability of the 50% DIP design alternatives

became more competitive. A sensitivity analysis was performed on the difference between the average on-peak and off-peak electricity prices to explore the impact of the increased occurrence of electricity price peaks. The results show that the greater this difference (at equal average price), the higher the profitability was for the 50% DIP alternatives. Furthermore, for an on-peak electricity price of $108/MWh, alternative 5-B became the most profitable 50% DIP design. However, one of the 100% DIP alternatives remained the most profitable at this peak electricity price (note that alternative 3-B now was most profitable).

The operations-driven cost model was used to track the impact of electricity load shifting on manufacturing cost and profit on an hourly basis during a day with an extreme electricity price event in a deregulated market (Figure 4.11).[1] Fixed on- and off-peak times were used to schedule the production of the TMP plant for this day. The resulting manufacturing cost profiles were calculated for the

[1]This day was September 3rd 2002, which had the highest peak electricity price since the liberalization of the electricity market in Ontario (Figure 4.11a) (data available at the IESO website: http://www.theimo.com/).

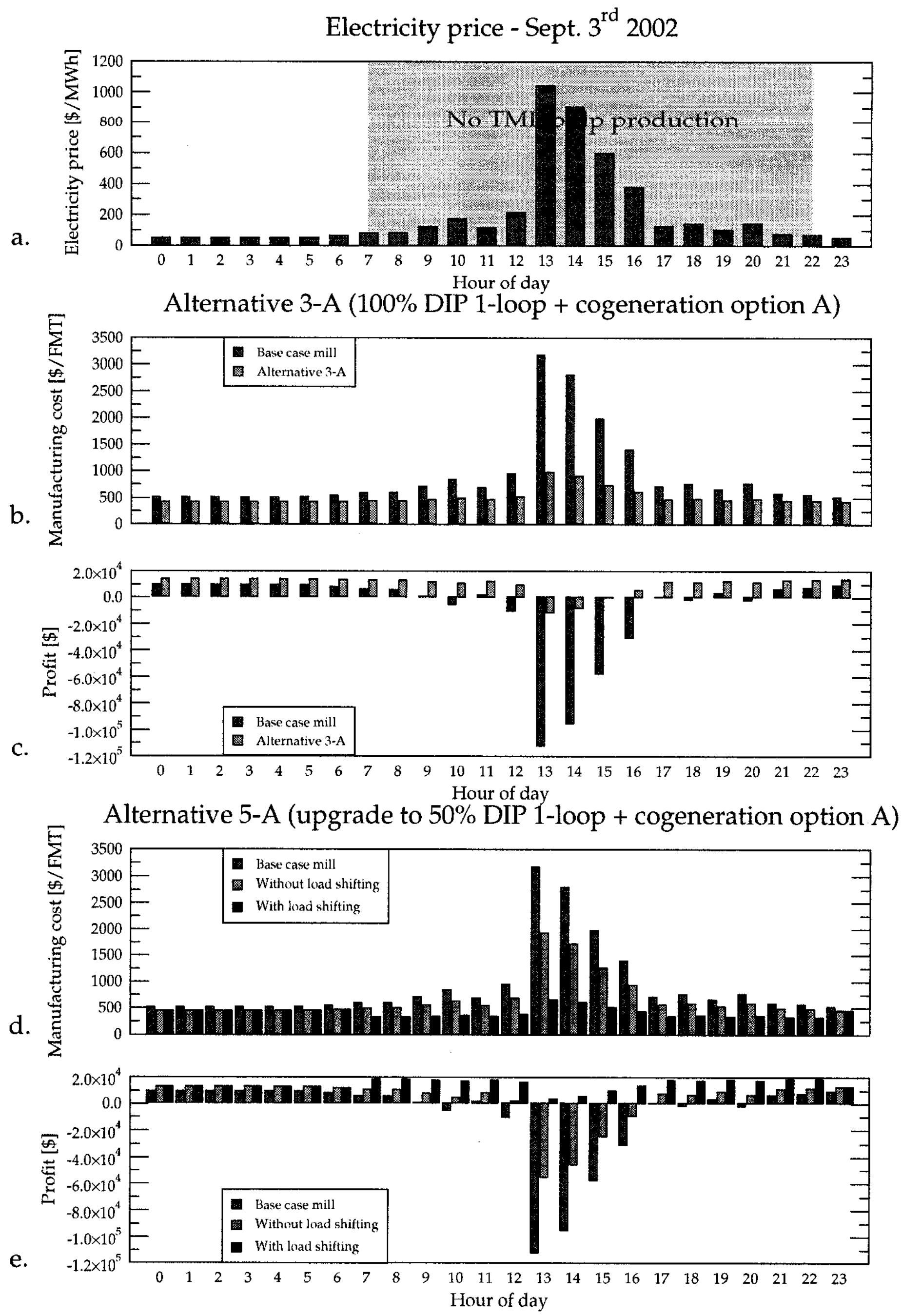

Figure 4.11: Impact of electricity load shifting during a day with an extreme electricity price event: a. Hourly electricity price; b+c, d+e. Manufacturing cost and profit for alternatives 3-A and 5-A, respectively

most profitable 100% DIP alternative, alternative 3-A, and for the most profitable 50% DIP alternative, alternative 5-A. For calculating the profit, a newsprint price of $735 per tonne was used. Electricity load shifting in alternative 5-A decreased the manufacturing cost significantly (Figure 4.11d) and as a result, the profit per hour was positive throughout the day despite the extreme electricity prices that occurred (Figure 4.11e). Alternative 3-A exhibited a negative profit during the hours with the highest electricity prices and had a lower total profit for this day than alternative 5-A (Figures 4.11b and 4.11c). Note that the 100% DIP alternatives are capable of dealing with high electricity prices because of their low electricity usage.

The analysis of process design changes benefits from having an operations-driven cost model based on ABC-like principles in place due to the systematic integration of process and cost data. The model focuses on process costs instead of product costs and is able to analyze the implications of incremental energy usage, increased process energy efficiency or more advanced operating strategies such as electricity load shifting. This leads to the identification of favorable operating conditions in order to increase the profitability of the retrofit design alternatives.

4.3.2 Supply chain-level analysis

The next step in the overall methodology involved using the cost and production information gathered via the operations-driven cost model in a supply chain-level analysis, that employed supply chain and LCA models (Figure 4.12). This was done for all of the retained design alternatives (Figure 4.5). The purpose of the supply chain-level analysis was to investigate how market conditions would impact the operations for each design alternative from an economic and environ-

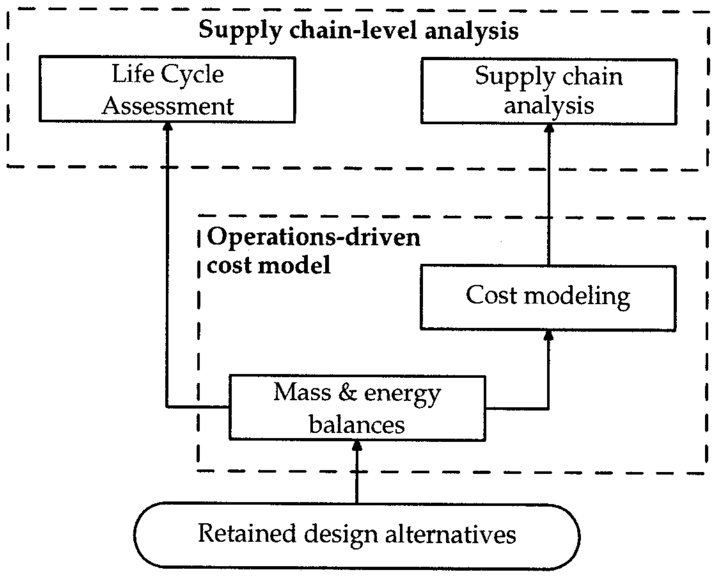

Figure 4.12: Use of information generated by the operations-driven cost model in the supply chain-level analysis

mental perspective at this level on a yearly basis. In particular, the model was used to address energy-related concerns.

The supply chain model maximized the annual supply chain profit. This profit was defined as the difference between the revenues from the sales of newsprint and cogenerated electricity, and the direct production costs, raw material and overhead costs. It considered the paper manufacturing process, the energy household of the mill, the supply of raw material and the delivery of newsprint. Inventory costs were not considered in this model. The model used production information generated by the mass and energy balances in order to characterize the manufacturing operations of the alternatives. Cost information included unit resource costs to calculate the raw material (wood chips, waste paper, wood waste and natural gas), supplies, chemicals and electricity costs.

The system boundaries of the LCA model contained all activities that were affected by the implementation of the design alternatives, whether or not these activities were within the boundaries of the newsprint life cycle. They mainly included the mill production processes and upstream activities to maintain them, e.g. chemical and fuel production as well as activities in other systems affected by changes in the system (e.g. paper disposal, other consumers of recycled fibres).

The LCA model used only production information, and characterized the environmental impact of the alternatives using four impact categories (human health, ecosystem quality, climate change and resources). The material flows that were expected to show significant changes were selected and the information was extracted from the mass and energy balances inside the operations-driven cost model. The LCA model characterized the different environmental impact changes for the design alternatives compared to that of the base case mill. Since the cost model was supplying only mill process data, it was necessary to complete these data with the most appropriate generic data for non-mill processes that characterized the other parts of the life cycle. An LCA was also completed for the BAT (Best Available Technologies) integrated newsprint mill. The BAT mill is based on information provided by IPPC (Integrated Pollution Prevention and Control) standards (European IPPC Bureau, 2001). The results of this LCA were also used in the subsequent decision making step (see section 4.3.3).

The annual supply chain profit and environmental impact improved for all design alternatives considered, when compared to the base case mill (Figures 4.13 and 4.14). The difference in supply chain profit between the alternatives was mostly due to the difference in the amount of cogenerated electricity. Furthermore, the design alternative with the highest profitability (Figure 4.5) did not have the highest supply chain profit: alternative 3-B had the highest annual supply chain profit, whereas alternative 3-A was most profitable (i.e. it had the

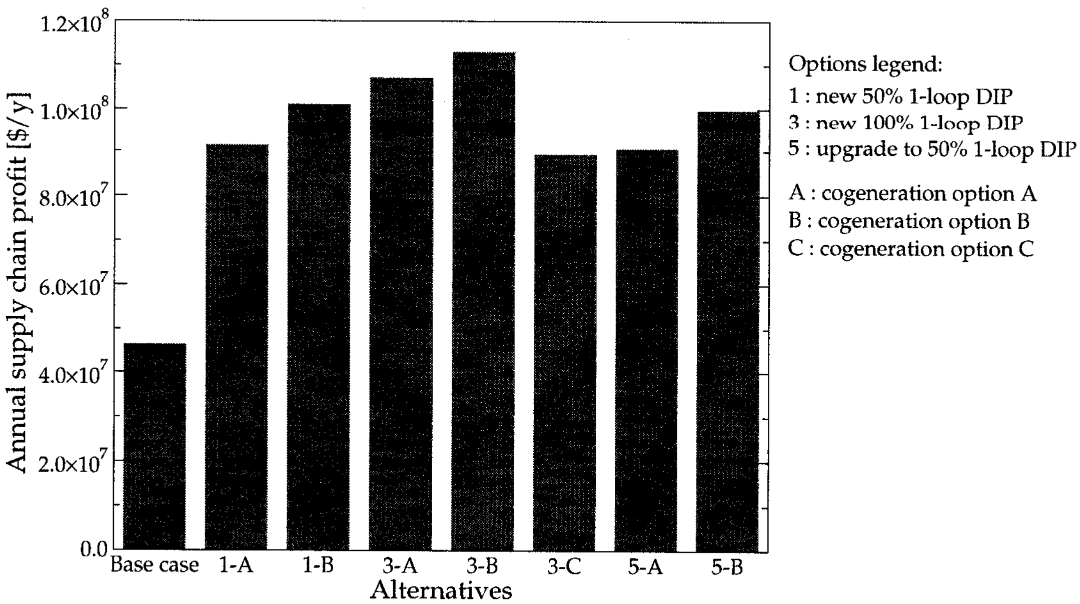

Figure 4.13: Annual supply chain profit for the retained design alternatives and the base case mill

highest IRR). Alternative 3-B achieved a higher annual profit due to a higher income from selling cogenerated electricity, but had a lower profitability because it required a higher investment (Figure 4.2). The increase in environmental performance of the alternatives can be mainly attributed to reduced TMP pulp production (50% DIP alternatives) or shutdown of the TMP plant (100% DIP alternatives) and the increase of cogenerated electricity. Consequently, alternative 3-B outperformed all other alternatives for each impact category, because the TMP plant was shut down and cogeneration option B had the biggest electricity generation capability.

The supply chain-level analysis resulted in the identification of an alternative (alternative 3-B) that outperformed all other alternatives based on the metrics that were employed. This suggests that alternative 3-B is the most sustainable design alternative, since the inclusion of the supply chain level analysis enlarges the system boundaries beyond the process (Bakshi & Fiksel, 2003). Furthermore,

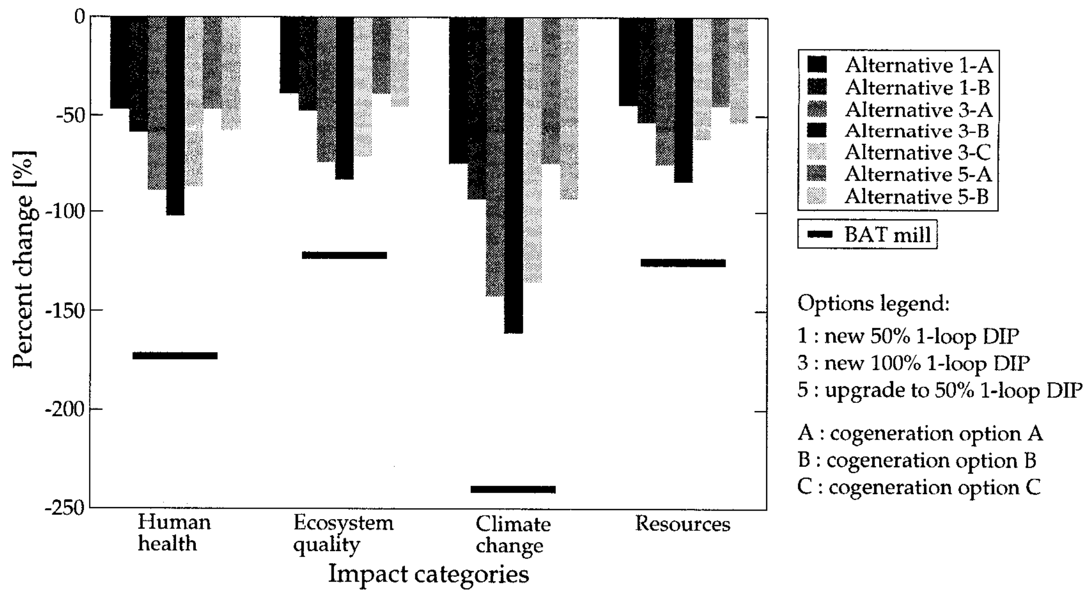

Figure 4.14: Results of the LCA for the retained design alternatives

the employed method first considered the retrofit design changes at the process level, followed by the inclusion of supply chain considerations. On the contrary, most design methodologies in the literature that consider the supply chain level first focus on the supply chain aspects and then consider the process design aspects. These methodologies were mostly applied to greenfield process design problems (see e.g. Hugo & Pistikopoulos (2005)).

A set of scenarios was defined in order to investigate the supply chain-level performance of the retained design alternatives under different market conditions. In one of these scenarios, the electricity price was varied. It was found that electricity price had a significant impact on supply chain profit (Figure 4.15). For the range of electricity prices considered, the base case mill design was the least favorable design and its annual supply chain profit declined much faster because of its higher electricity use in the TMP plant when compared to other retained design alternatives. Likewise, the supply chain profit for the 50% DIP design

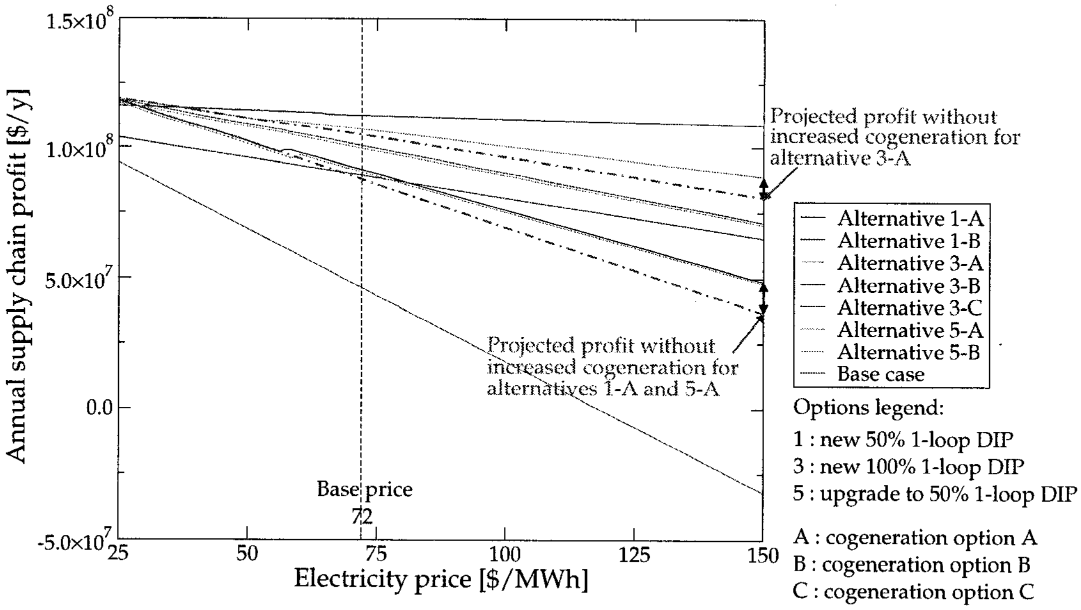

Figure 4.15: Annual supply chain profit for the base case mill and design alternatives with varying electricity price

alternatives (alternatives 1-A, 1-B, 5-A and 5-B) declined more rapidly with increasing electricity price than for the 100% DIP design alternatives (alternatives 3-A,B and C). It should be noted that there was no change in total newsprint production or price.

The electricity price affected the steam production in the boiler plant, especially in the case of the alternatives with cogeneration option A. This subsequently affected the wood waste supply to the boiler plant (Figure 4.16). At lower electricity prices, these design alternatives were more profitable when producing only the steam needed for the process, whereas at higher prices they became more profitable when producing excess steam for increased electricity generation. The increased use of wood waste did not lead to a significant increase in the profit for alternatives 1-A, 3-A and 5-A (Figure 4.15). The revenue due to more electricity generation was largely offset by the higher electrical cost for

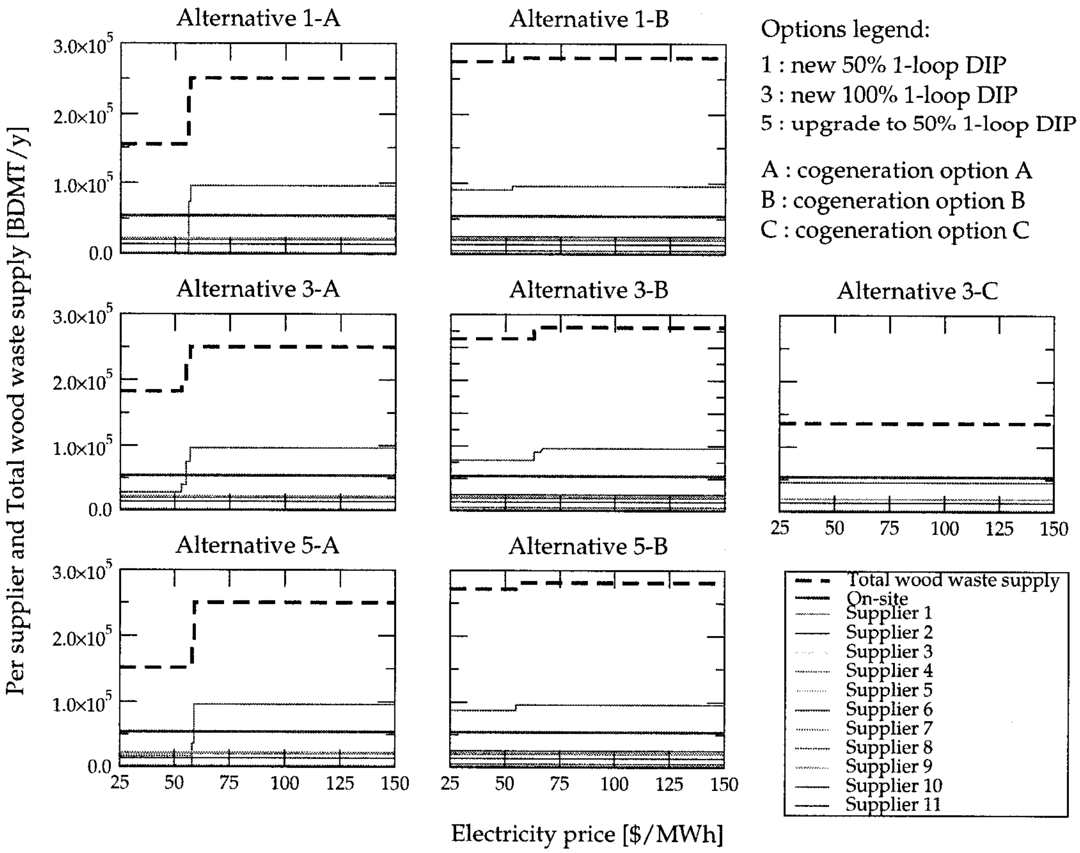

Figure 4.16: Wood waste supply for the retained design alternatives with varying electricity price

running the process and the cost of extra wood waste used. However, the profit for these alternatives declined at a slower rate at higher electricity prices due to the increase in electricity generation. It should be noted that the environmental impact did not change significantly because of varying wood waste use, mostly due to the absence of natural gas in the fuel mix used in the boiler plant at both lower and higher electricity prices.

As became clear from the electricity price scenario analysis, wood waste use and availability play an important role in the supply chain optimization of certain alternatives. Therefore, wood waste availability under competitive and non-

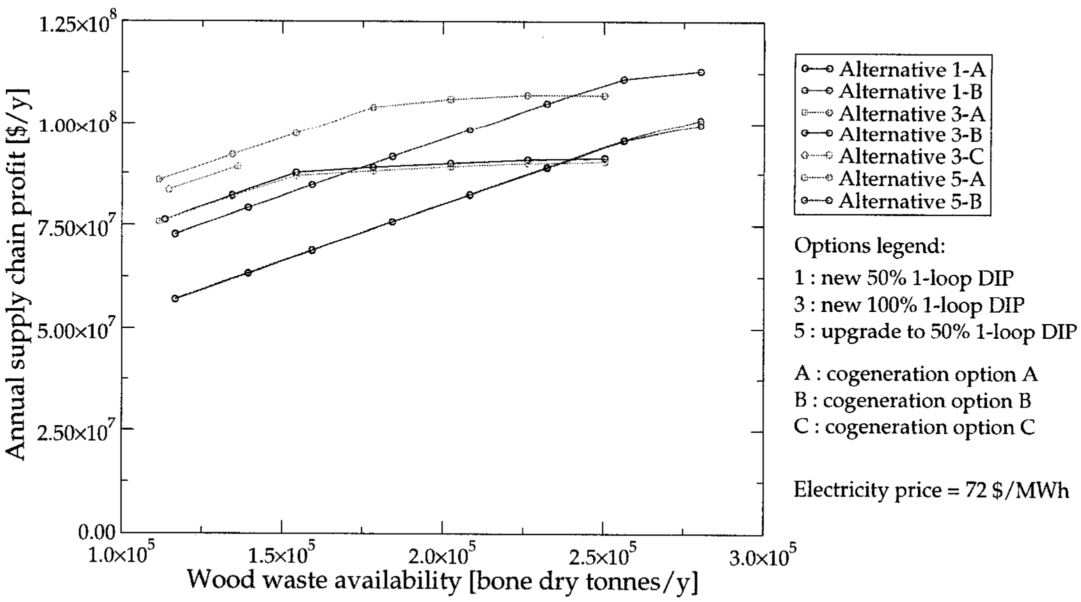

Figure 4.17: Annual supply chain profit for the retained design alternatives with varying wood waste availability, no competition for wood waste

competitive market conditions was varied. Under non-competitive conditions, it was assumed that the wood waste price remained at the base case value, and wood waste availability varied due to technical reasons (e.g. the closure of a sawmill). At first, a decrease in wood waste availability had a minor effect on the supply chain profit for the retained design alternatives with cogeneration option A (Figure 4.17 (electricity price is 72 $/MWh)). However, this effect was attenuated when natural gas was required as a replacement fuel to compensate for the lower wood waste availability. For alternatives 1-A and 5-A this occurred at $1.5 \cdot 10^5$ bone dry tonnes/y of wood waste and for alternative 3-A at $1.8 \cdot 10^5$ bone dry tonnes/y. Below these availabilities, there was no excess steam production for cogeneration, because the natural gas cost for producing this excess steam outweighed any profit that could be made with the additional electricity generation. The alternatives with cogeneration option B used natural gas almost as soon as wood waste availability decreased, because electricity generation was maintained at a high level. In these cases, the profit from generating electricity outweighed the cost of steam production, even though this resulted in a faster decline of the annual profit. As a result, alternatives 1-B, 3-B and 5-B had a lower profit than the other alternatives at low wood waste availability. These results depended on the price differences between electricity and fuel costs. For instance, at an electricity price of 35 \$/MWh and low wood waste availability, alternatives 1-A and 5-A (both 50% DIP alternatives) became more profitable than alternative 3-A.

In the non-competitive scenario for wood waste availability, the design alternatives showed an increase in the resources impact category for all alternatives and thus a lower environmental performance at low wood waste availability, while the other indicators stayed practically the same (Figure 4.18). This was due to increased natural gas use. Therefore, from a resource use standpoint, lower wood waste availability was both economically (Figure 4.17) and environmentally undesirable. It should be noted that the resource impact category for alternatives 3-A and 3-B were almost equal at low wood waste availability: the higher use of natural gas neutralized the advantage of more electricity generation in alternative 3-B.

The competitive wood waste scenario was defined as the case where all recoverable wood waste was used (90,000 bone dry tonnes/y, which is the base case mill usage) with additional supply needing to be deviated from other systems. As a result, this extra wood waste was purchased at a higher price. It was assumed that this led to increased use of coal to maintain sufficient electricity generation in other systems. For all alternatives, the annual supply chain profit decreased only slightly at higher wood waste prices, because the higher cost of wood waste was still low compared to the cost of the other raw materials and natural gas. On the other hand, competitive conditions for wood waste had a greater impact

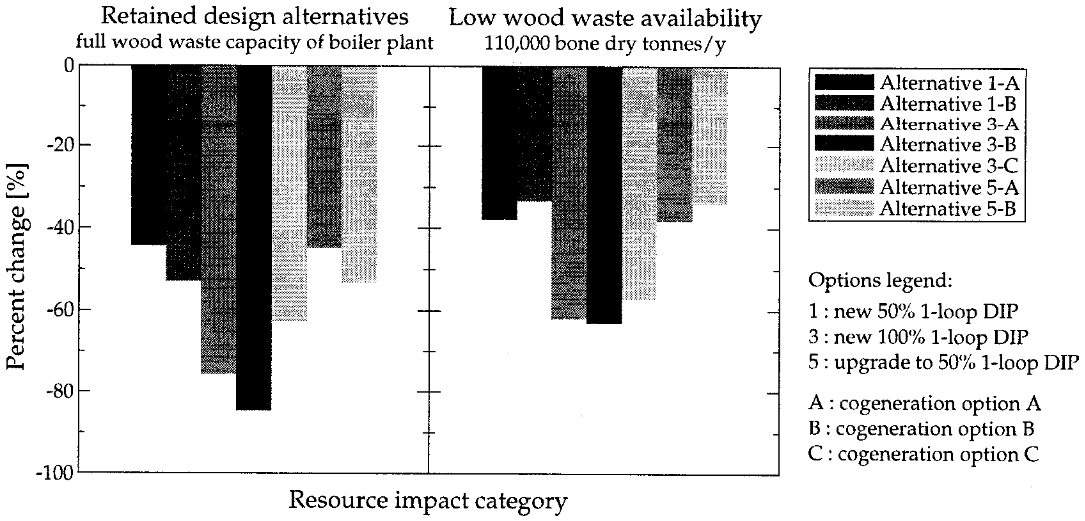

Figure 4.18: Resource impact of the design alternatives at low wood waste availability under non-competitive market conditions: 110,000 bone dry tonnes/year available at base case price

on the environmental performance of the alternatives, especially for the human health category at both high and low electricity prices (Figure 4.19). At higher electricity prices, this scenario showed a deterioration of the human health impact for the 50% DIP alternatives compared to the base case mill. This was due to the increased use of coal for electricity generation in the systems from which the extra wood waste was deviated. If a fuel other than coal had been assumed to replace wood waste in these systems, these results would have been less dramatic.

The scenario analyses provided further insight into the behaviour of the design alternatives under varying market conditions. These scenarios resulted in changes in the mass and energy balances, and in the cost information at the process level. By using the approach shown in Figure 4.12, these changes were also reflected at the supply chain level.

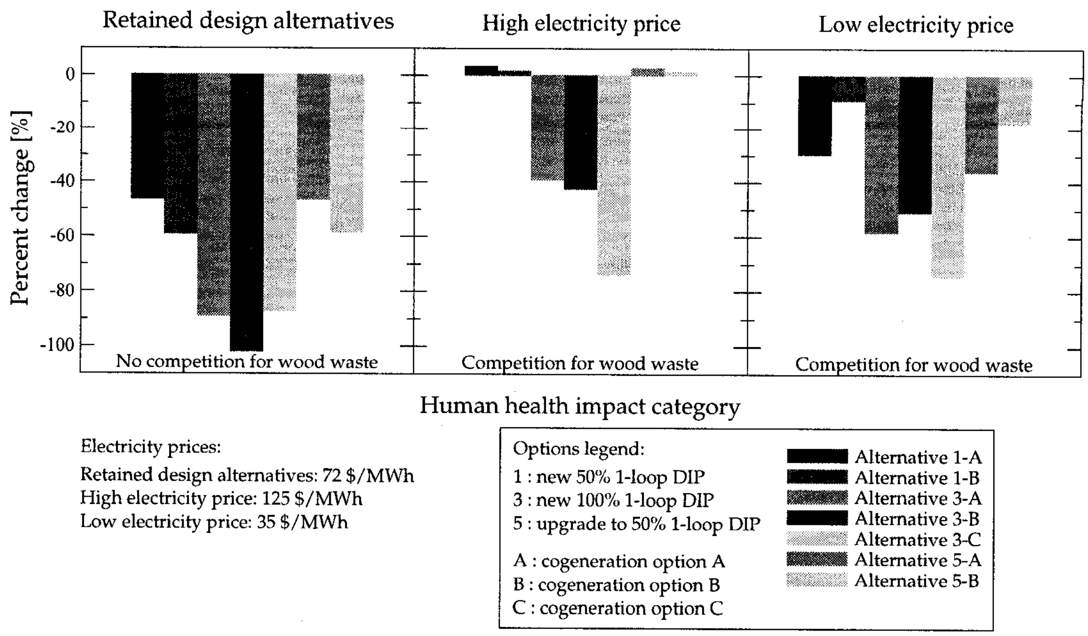

Figure 4.19: Human health impact of the retained design alternatives for wood waste availability under competitive market conditions

4.3.3 Multi-Criteria Decision Making panel

The last step in the overall design methodology was carrying out a Multi-Criteria Decision Making (MCDM) panel. Benefits of using MCDM in a design context are (Hazelrigg, 1998, 1999):

- It rationalizes the design decision process
- It provides a systematic approach to design decision making
- It guides the decision maker(s) in coming to a rigorous and more balanced decision based on multiple decision criteria.

The MDCM panel might replace the classical capital approvals process in a company for projects of this magnitude. The decision method was based on Multi-

Table 4.2: Economic decision criteria

Criterion	Attribute	Justification for use
Investment	Total capital cost [$]	The pulp and paper industry has limited access to capital
Profitability	Internal Rate of Return [%]	Its target value is usually set by a company
Energy economics	Electrical self-sufficiency [%]	Reflects the mill's independence on external energy sources
Supply chain profit	Annual supply chain profit [$/y]	Market conditions may have an impact on the operations, the supply of raw materials or the demand of newsprint

Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1976). MAUT provides a mathematically robust decision framework that distinguishes between the importance of criteria (decision weight) and the preference for a decision attribute value (utility). However, it has rarely been used for design decision making in chemical engineering.

The panel consisted of five panel members with diverse backgrounds: two had a corporate pulp and paper industry background, one was an engineering consultant, one was an LCA expert and finally, one was expert in sustainable development. The panel evaluated the design alternatives based on a set of environmental and economic decision criteria whose attributes were calculated using the operations-driven cost and supply chain-level models.

The environmental criteria included the impact categories that resulted from the LCA (human health, ecosystem quality, climate change and resources). The economic criteria were selected based on their relevance with respect to the design decision problem (Table 4.2). All criteria were placed at the same decision level in order to increase the panel members' awareness of the different trade-offs involved (Figure 4.20). At the same time, this avoided comparing overly aggregated economic and environmental scores, which might lead to an overemphasis of economic objectives.

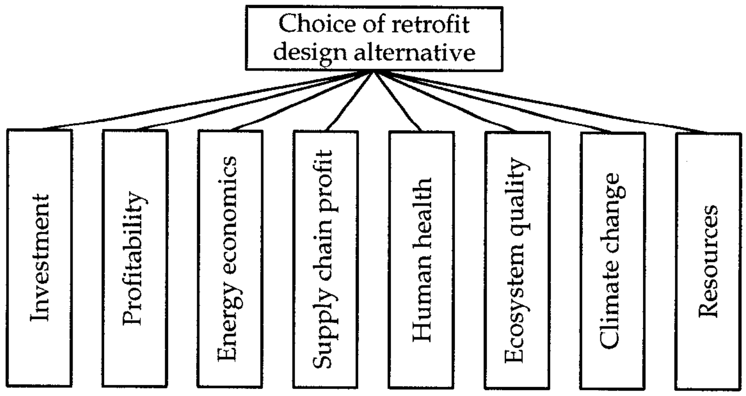

Figure 4.20: Decision structure for the retrofit design problem

The utility functions, that quantify the preference for an attribute (metric) value, were assumed to be linear between upper and lower bounds (eq. (4.5)):

$$u_i(x_i) = \begin{cases} 0 & \text{if } x_i < x_i^{low} \\ mx_i + b & \text{if } x_i^{low} \leq x_i \leq x_i^{up} \\ 1 & \text{if } x_i > x_i^{up} \end{cases} \tag{4.5}$$

These bounds, x_i^{low} and x_i^{up}, were chosen for each attribute such that all outcomes were within the range or were bounded by targets common to the pulp and paper industry. More specifically, for the environmental attributes, the targets were set by the outcomes of the LCA of the BAT mill (Figure 4.14). The bounds for certain economic attributes were defined by setting their targets. For instance, the upper bound for the IRR was set at a target value of 20%, an acceptable value for the IRR in the pulp and paper industry where only projects with significant rate of return are considered for approval.

The objective of the panel was to establish weights for each criterion, i.e. the importance of each of the criteria in taking a decision regarding the best design alternative. This was done using the trade-off method (Beinat, 1997). The panel members first established profitability (IRR) as the most important decision cri-

Table 4.3: Average trade-off attribute values and standard deviation for the criteria vs. profitability (n=5)

Decision criteria	Average trade-off attribute value vs. IRR	Standard deviation
Profitability	n/a	n/a
Investment	20	0
Energy economics	15.6	0.9
Supply chain profit	15.6	1.3
Human health	15.2	3.9
Ecosystem quality	16.4	4.0
Climate change	17.6	5.4
Resources	18.2	2.4

terion. Other criteria were compared against IRR. Decision weights were calculated using trade-off values that were determined by averaging the individual answers of the panel members (Table 4.3). The closer the trade-off value was to the IRR target value (20%), the less the panel members were willing to give up on the IRR. Profitability was considered as important as the other decision criteria together, and economic criteria constituted 70% of the total decision weights (Figure 4.21).

The panel members had difficulty trading off environmental criteria against profitability due to the difficulty of interpreting these criteria and consequently, quantifying them. For instance, only one panel member was willing to trade off a significantly lower profitability to obtain better performance for the climate change criterion. The other panel members argued that there are already mechanisms in place which stimulate businesses to reduce their green house gas emissions. These mechanisms thus would impact profitability and make the climate change criterion redundant. The economic criteria showed a lower difference of opinion between the panel members. One surprising result was that the investment criterion was not given any weight. It was argued that smaller investment projects are often more risky and therefore require a higher IRR.

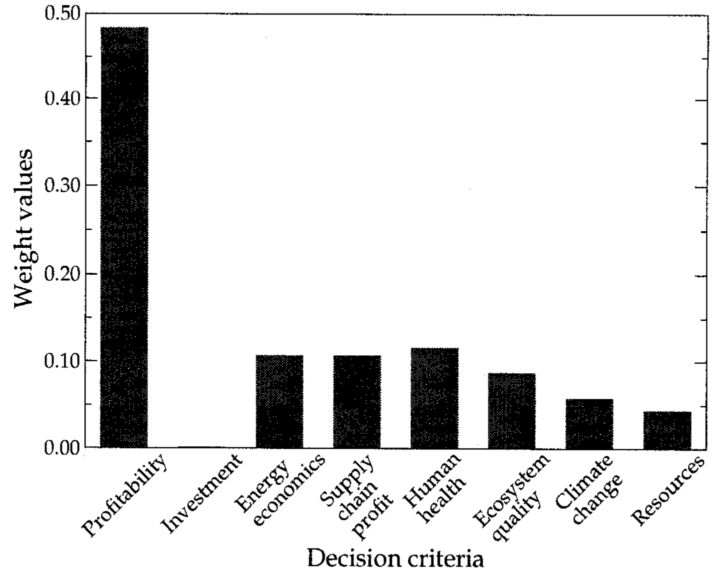

Figure 4.21: Decision weights based on average trade-off values

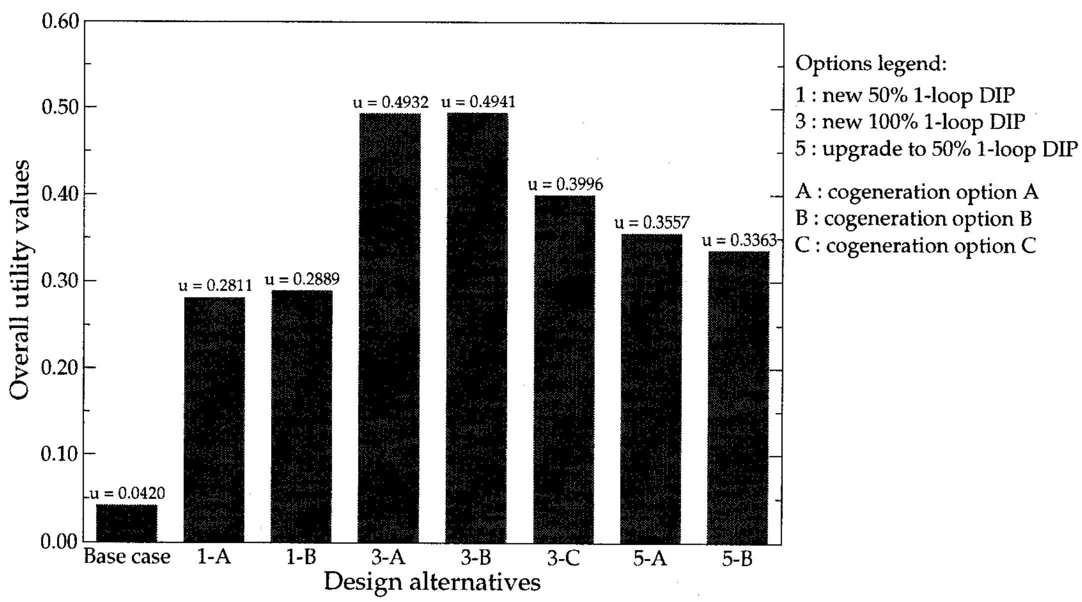

Figure 4.22: Utility values for the retained design alternatives and the base case mill

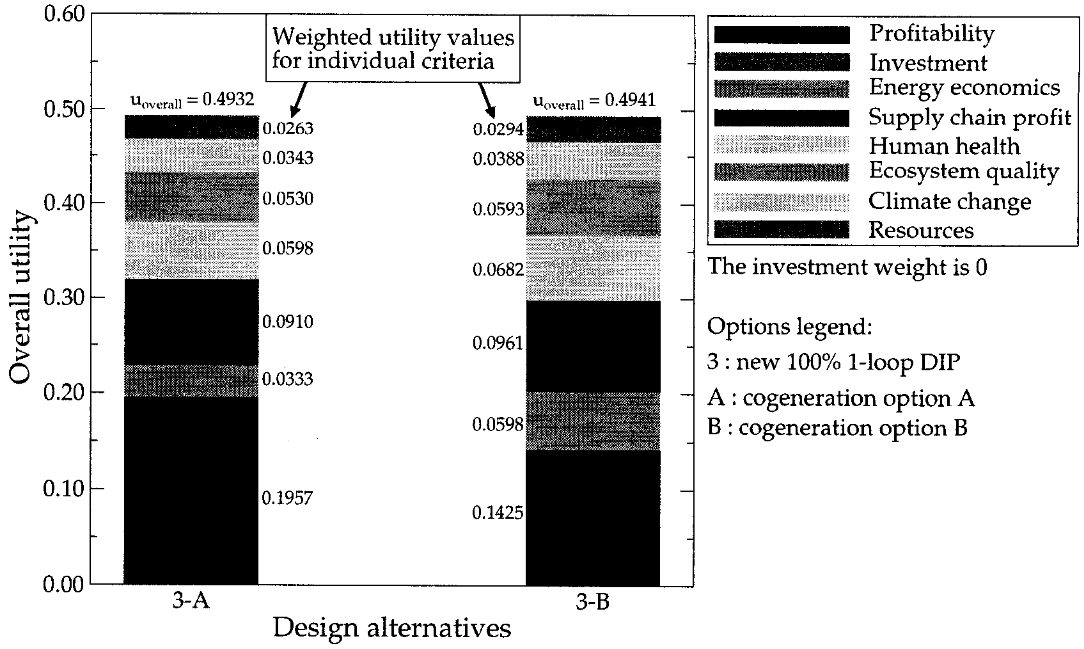

Figure 4.23: Comparison of alternatives 3-A and 3-B split up by criteria

The overall utilities for the design alternatives were calculated using the average decision weights (Figure 4.22). Alternative 3-B was slightly preferred over alternative 3-A. Alternative 3-A outperformed alternative 3-B for profitability, but the latter compensated for this by outperforming the former in all other criteria (Figure 4.23). This was due mostly to the higher electrical self-sufficiency of alternative 3-B (Figure 4.6) and the resulting economic and environmental improvements. The use of criteria whose attributes were calculated with the operations-driven cost and supply chain-level models, besides the profitability criterion, identified alternative 3-B as the preferred alternative. Had profitability been used as the sole criterion, as is often done in conventional design decision making, alternative 3-A would have been the preferred alternative. It can thus be argued that a more sustainable design alternative (alternative 3-B) was selected (see section 4.3.2) due to the inclusion of supply chain-level criteria.

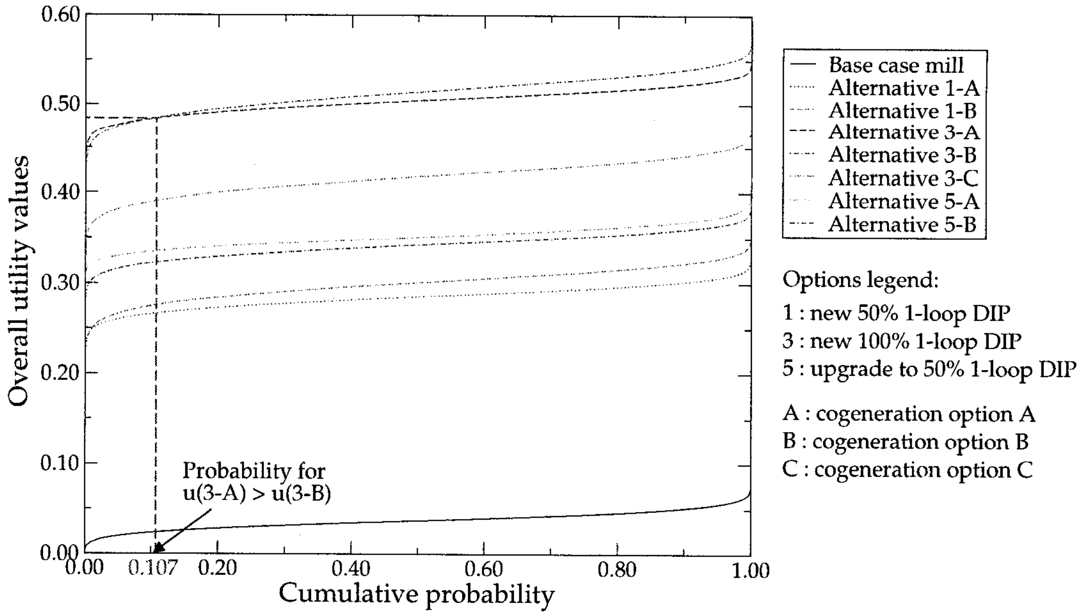

Figure 4.24: Results of the Monte Carlo simulation for the overall utility of the retained design alternatives

A sensitivity analysis was carried out by employing a Monte Carlo analysis (Butler, Jia, & Dyer, 1997). It was assumed that the trade-off attribute values were normally distributed and truncated at their lower and upper bounds. The average trade-off attribute values and their standard deviations were used as the parameters of the probability distribution functions (Table 4.3). The outcomes of the sensitivity analysis for the overall utility for each design alternative demonstrated that the initially calculated utility values (Figure 4.22) adequately reflected the ranking of the alternatives according to the preferences of the panel members (Figure 4.24). The outcome of the Monte Carlo analysis showed the same ranking, and there was no overlap of the cumulative probability values with the exception of the two most preferred design alternatives, alternatives 3-A and 3-B. This overlap showed that in approximately 90% of the possible outcomes, alternative 3-B was preferred over alternative 3-A. Since the overall utilities for these two alternatives based only on the average decision weights were very close (Figure 4.22), this information would help in making the final decision.

So far the chemical engineering community has mostly focused on multi-objective optimization (MOO) when considering more than one decision objective. MOO allows for the determination of optimal design alternatives based on these objectives but cannot determine the best alternative based on the decision makers preferences. Using a MCDM approach for design decision making enables the decision maker(s) to systematically consider multiple decision criteria in order to determine the preferred design alternative. Furthermore, it provides a systematic approach for the consideration of economic and environmental objectives at the supply chain level, whereas in a classical techno-economic design approach, environmental considerations are used only as design constraints at the process level. This may lead to more sustainable design decision making due to the inclusion of the of these higher-level aspects.

4.3.4 Conclusion

This chapter outlined the implementation of the design methodology, and its results related to the case study involving the implementation of increased DIP pulp production and cogeneration at an integrated newsprint mill. First, the operations-driven cost modeling approach was applied to characterize the existing mill and the design alternatives at the process level. Next, a supply chain-level analysis was used to obtain information about the impact of the design alternatives. Finally, process- and supply chain-level decision criteria were used in a MCDM panel to evaluate the alternatives and determine the preferred one. The proposed methodology enables decision makers to use process- and supply chain-level decision criteria in order to make more balanced decisions. The operations-driven cost model results in more transparent cost information about the design alternatives at the process level and allows for more advanced analysis when compared to the classical design approach. This is due to the ABC-like structure of the model which emphasizes the process costs, whereas the classical approach focuses on the product cost. Using the process-level information, economic and environmental objectives are systematically addressed at the supply chain level which is not part of the classical design approach. This results in an expansion of the system boundaries which results in the identification of more sustainable design alternatives. The MCDM panel systematically uses economic and environmental decision criteria for better and more balanced design decision making whereas the classical approach typically uses economic criteria only.

The case study that was used in this work demonstrated that the best design alternative changed as more knowledge was used. At the process level, alternative 3-A was the best alternative due to its profitability. However, due mostly to its higher electricity generation potential, alternative 3-B outperformed alternative 3-A at the supply chain level. Nevertheless, the MCDM panel valuated these two alternatives almost equally, emphasizing the importance of profitability compared to the other decision criteria that were used. Sensitivity analysis showed a more distinct preference for alternative 3-B.

CHAPTER 5

GENERAL DISCUSSION

A scientist's aim in a discussion with his colleagues
is not to persuade, but to clarify.
Leo Szilard (1898–1964)

In recent years, Information Management Systems (IMS) have gathered massive amounts of process, cost and environmental data at manufacturing sites, and in the case of this work an integrated newsprint mill. However, the tools that are currently used focus mostly on *ad hoc* application of these data, while process systems engineering (PSE) tools may help to more fully exploit the availability of the data. The goal of this work, therefore, was to build a methodology that would use these data and PSE tools in order to make better retrofit design decisions. At the outset of this work, a framework was defined where a so-called bottom-up approach was proposed in order to exploit the available data, by extracting information at the process and the supply chain level that can be used for operational and design decision making (Figure 5.1). The most relevant information was then selected to be used as input for multi-criteria de-

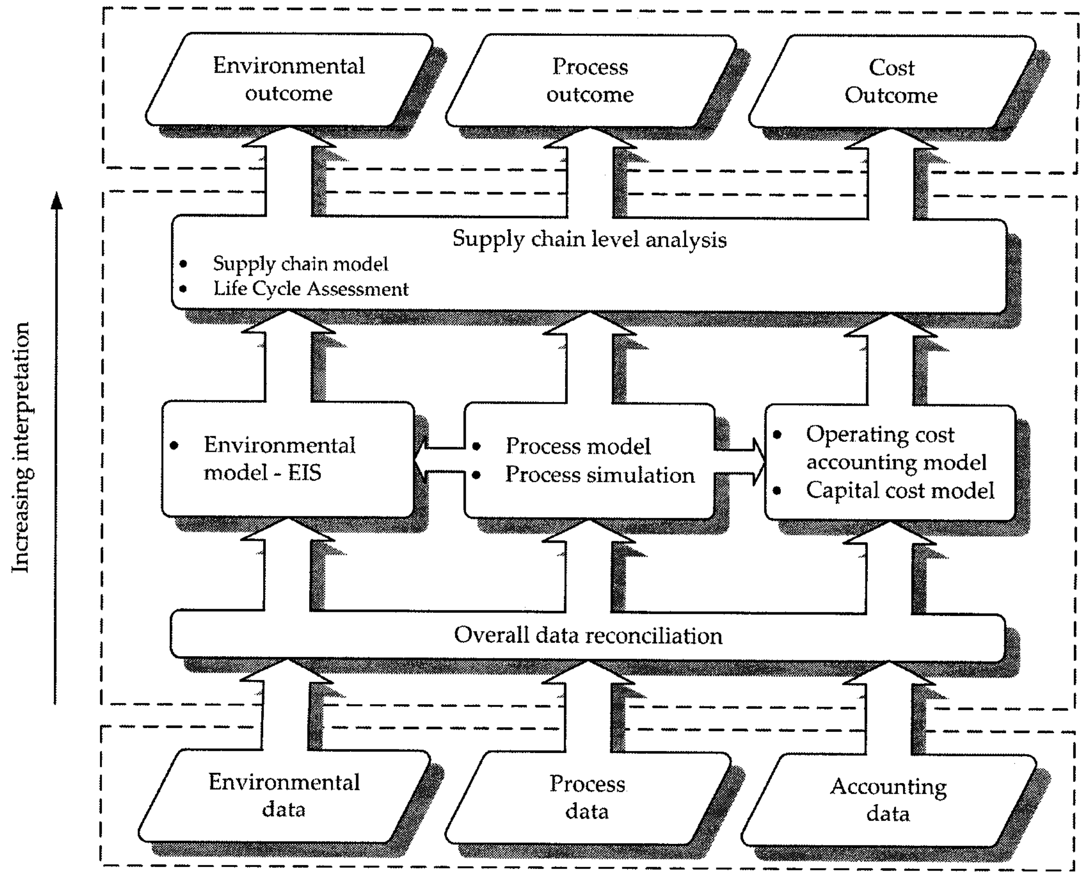

Figure 5.1: Initial framework for the use and manipulation of process, cost and environmental data

cision making (MCDM) in order to identify the preferred design alternative. In the course of the work, an operations-driven cost model and supply chain-level models were developed and applied to a retrofit design problem, respectively, and an MCDM panel was carried out, in order to demonstrate the use of this framework (Figure 3.3).

Operations-driven cost model

The application of the operations-driven cost model (Figure 4.1) to extract information from process and cost data for retrofit design decision making has several advantages, and some improvements with respect to a conventional techno-economic study that was also carried out as part of the overall methodology.
The operations-driven cost modeling approach, that is founded on Activity-Based Costing-like (ABC-like) principles, uses data that are readily available from the IMS implemented at mills. The integration of the process and cost data serves as the basis for reconciling these data. It increases the visibility of the manufacturing costs in the different parts of the facility under study, due to the model's process perspective, and how these costs change for each design alternative. In the context of retrofit process design, this implies that the process and cost data are synchronized, i.e. the cost and process flows across the system correspond with each other. Therefore, this integration allows for a more in-depth description of the main manufacturing operations. This is an improvement over the conventional techno-economic study in which the process and cost models and data are typically maintained separately.
The Process Work Centres (*PWCs*), constituting the existing design and the design alternatives respectively, are defined based on the process and cost data that are available, and on the design changes that are proposed. The resources that are used in the process are directly related to the activities that are performed in these *PWCs*. The mass and energy balances, that calculate resource use, feed the *PWCs* with the appropriate data that reflect the conditions under which each *PWC* operates and studies the effect of changing operating conditions, as was done for the marginal cost analyses. On the other hand, in conventional techno-economic studies, the resources are not directly related to the activities that take place in the process units. Rather, the costs are directly related to the product, in

this case newsprint paper. As a result, the marginal cost analyses that were carried out in this work cannot be performed, because in a techno-economic study the focus is on the product costs, not the process costs.

Furthermore, the *PWCs* can accomodate specific models that describe changes in the operating strategy. For instance, in this case study, an electricity load shifting model was introduced to the TMP *PWC* in order to study the effect of this strategy on the profitability of a certain design alternative. Since the resource costs are better traced to the defined *PWCs*, significant benefits could also be achieved if the model was used and maintained by process and operations engineers at a mill. The model would help them identify opportunities for process design improvements. Using the data that are gathered by the IMS in the model may result in the identification of large investment projects, but may also lead to the implementation of smaller projects in order to increase the energy efficiency of the mill. The model can also be used to characterize the performance (e.g. profitability) of a project under different market conditions, e.g. varying electricity or natural gas prices, or varying fibre prices. In a conventional techno-economic study, the concept of the *PWC* does not exist.

Supply chain-level analysis

The supply chain-level analysis is carried out using supply chain and LCA models. These models use process and cost information that are generated by the operations-driven cost model, linking the process level to the supply chain level in a bottom-up manner (Figure 4.12). Therefore, this analysis yields information about the supply chain-level performance (economic and environmental) of the retrofit design alternatives based on process-level data. As such, this approach first considers retrofit design changes at the process level, followed by the inclusion of the supply chain considerations. As part of the supply chain-level analysis, scenarios can be defined in order to obtain more information about the performance of a design alternative under different market conditions. The same approach can be followed in order to reflect performance changes at the supply chain level due to operational changes at the process level that are invoked by these scenarios. Scenario analysis shows trends in the criteria that are useful for decision making, but when taking account of multiple criteria, it is necessary to carry out a decision analysis in order to determine their relative importance.

Legal regulations force the design alternatives to be environmentally compliant at the process level, and thus act as constraints on the feasibility of them. This is the focus of Environmental Impact Studies (EIS) (Figure 5.1). In this work, an EIS was part of the conventional techno-economic study that was carried out and thus, the alternatives that were considered, were guaranteed to be environmentally compliant at the process level. However, the supply chain-level analysis may bring to bear trade-offs between environmental and economic criteria at this level, since both are used to reflect the decision objectives. This adds more insight and information, but also more complexity to the decision making process. This is another reason for carrying out a decision analysis that will help the decision maker(s) to identify their preferred alternative. At the same time, more sustainable design alternatives can be identified due to the expansion of the system under study. However, this expansion may result in introducing more uncertainties to the evaluation of the design alternatives.

Multi-criteria decision making panel

Before the decision panel was carried out, the decision criteria and their attributes, the decision structure and utility functions were selected. Ideally, each of these elements should be discussed with the decision panel members before the actual panel occurs. Unfortunately, due to time constraints it was not possible to do this. Therefore, several choices had to be made related to these elements of the decision method.

The selection of the decision criteria and their attributes (metrics) is an important consideration. They need to correctly reflect the objectives of the decision and the consequences of choosing a design alternative. Compared to the decision process used in conventional retrofit process design, the current decision method is better able to consider sustainability, because of the definition of economic and environmental objectives instead of a sole economic objective as is usually done in a conventional techno-economic study. Besides some process-level criteria and attributes, this results in the selection of supply chain-level criteria and attributes that reflect both these objectives. The criteria and attributes also need to be unambiguous and understandable so that the panel members do not have difficulties in interpreting their significance. Furthermore, the panel members need to be made aware of the fact that, although criteria may physically depend on each other, this does not mean that such criteria are redundant for the decision making process. In other words, the physical dependence between criteria should be considered separately from preference dependence between criteria.

The decision structure may also have a significant impact on the outcome of the decision panel, i.e. which design alternative is selected. When trading off between one aggregated economic and one aggregated environmental indicator, the economic indicator may be overweighted. This is due to the fact that environmental improvement is usually initiated by setting regulations and thus considered as a constraint on the operation of a mill instead of as an objective. Therefore, it is proposed in this work to situate all criteria at the same level. On the other hand, this may lead to difficulties in trading off between the economic and environmental criteria because the panel may find it hard to monetize environmental criteria.

The goal of an attribute utility function is to quantify the preference of the decision maker for an attribute value and his/her behaviour towards risk for the criterion involved. This is reflected in the shape of the function. A concave utility function reflects risk averse behaviour, whereas a convex utility functions reflects risk prone behaviour (Keeney & Raiffa, 1976). Therefore, the shapes of the attribute utility functions impact the final outcome of the decision. Furthermore, the domain of attribute values over which the utility function is valid may be prone to discussion due to different target values used by the decision makers. Therefore, the shape of the utility functions should either be determined as part of the decision panel or be discussed in-depth with the panel members if the functions have already been selected before weighting the criteria.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Reasoning draws a conclusion,
but does not make the conclusion certain,
unless the mind discovers it by the path of experience.
Roger Bacon (c. 1214–1294)

6.1 Contributions to the body of knowledge

Construction and demonstration of a novel retrofit design methodology

This methodology extracts process- and supply chain-level information from process, cost and environmental data available from information management systems for retrofit design decision making using process systems engineering tools. This is done by following a bottom-up approach using the following three steps:

1. The application of an operations-driven cost modeling approach based on Activity-Based Costing (ABC)-like principles that characterizes the retrofit design alternatives at the process level
2. Deduction of the performance of the design alternatives at the supply chain level, economically as well as environmentally, using supply chain and Life Cycle Assessment (LCA) models and process-level information
3. Retrofit design decision making by running a Multi-Criteria Decision Making (MCDM) panel that selects the preferred design alternative based on process- and supply chain-level criteria.

Development and application of an operations-driven cost modeling approach

The operations-driven cost modeling approach enables the user to model the design alternatives based on the data that are available, and the purpose of the model. More specifically:

- Process Work Centres are defined that represent the process units inside a design alternative and determine the level of detail of the cost model
- The Activity-Based Costing-like approach allows for accurate tracing of resource costs to the Process Work Centres. This results in a focus on the process costs, rather than the product costs.
- The approach allows for detailed integration and reconciliation of process and cost data, in a design context guaranteeing the synchronization of the process and cost flows in the model

- Advanced cost analysis for decision making purposes such as marginal cost analysis, energy efficiency studies and analysis of operational strategies can be readily implemented inside the model
- The model is able to identify favorable operating conditions and/or strategies for the implementation of increased DIP pulp production and cogeneration at an existing integrated newsprint mill.

Application of supply chain-level models using process-level information

The proposed bottom-up approach for the use of process and cost data leads to the interpretation of these data at a higher level, in this case the supply chain level. The retrofit design changes at the process level are first considered, followed by the inclusion of supply chain considerations. Expanding the scope of the conventional retrofit design process by including the supply chain level using this approach, results in the following:

- The ability to trade off between economic and environmental objectives at this level instead of only considering an economic objective that is subject to environmental constraints at the process level
- Using scenario analyses to determine the impact of market conditions on the operations of the design alternatives and the supply chain. This impact is determined at both levels using process and cost data, i.e. the scenarios are also characterized using the bottom-up approach for the interpretation of the process-level data under different market conditions
- The identification of more sustainable design alternatives due to the expansion of the system boundaries beyond the mill.

Evaluation of the design alternatives by running an MCDM panel

Carrying out an MCDM panel allows for the systematic evaluation of design alternatives and selection of the preferred alternative using process- and supply chain-level decision criteria in order to select a design alternative:

- Multi-Attribute Utility Theory (MAUT) is used as the theoretical framework within which the decision panel is carried out
- Metrics that are calculated using the operations-driven cost and supply chain-level models are used as attributes for the criteria, with the goal of selecting a more sustainable alternative
- The decision structure places all criteria at the same hierarchical level, avoiding the trade-off between an aggregated economic and environmental indicator that would result from grouping these two kinds of criteria
- Monte Carlo analysis of the panel members' trade-off values refines the decision analysis. The probability of one alternative outperforming another may be a deciding factor
- The final decision may change due to the use of multiple criteria instead of the use of only the alternatives' profitability as decision criterion as is typically done in conventional techno-economic studies.

6.2 Future work

Operations-driven cost modeling for retrofit process design

The cost model that was constructed for this work considered only one cost object, the newsprint product. However, the model could also be applied to a design problem with multiple products such as in the case of a fine paper mill or in the implementation of a biorefinery concept at an existing mill. This last item in particular may be an interesting study due to the diversity of the products that may be produced from a biorefinery. The model could also be applied to study the cost improvements of more detailed energy efficiency studies than was done in this work.

The operations-driven cost modeling approach could be used to generate risk- or sensitivity-based cost metrics in order to take into account variations of design parameter values (e.g. process efficiencies) using the available process data. These variations could also be taken into account in the marginal cost analysis.

Supply chain-level analysis

The supply chain-level analysis could be expanded to include multiple production sites in order to optimize the supply chain network at the enterprise level. Cost models would also have to be constructed for these other sites and the process and cost information of all these sites would need to be merged inside an overall supply chain model. LCA models would also need to be constructed for the other sites in order to determine the environmental impact of the complete supply chain network. The impact of a large-scale retrofit design project, at one or more sites could then be validated at the enterprise level.

The supply chain optimization did not result in paper machine shut downs for the market conditions that were considered reasonable on a yearly basis in this work. However, such conditions may occur in the future and would impact the cost structure at the process level. Therefore it would be interesting to look at enhancing the interaction between the operations-driven cost and supply chain level models.

The supply chain-level models could also be used to calculate risk- or sensitivity-based metrics. Due to the bottom-up approach, these could be based on variations of parameter values at the process level as well as at the supply chain level (e.g. availability of fuels or raw materials).

Decision making method

Several elements of the decision making method were determined before the MCDM panel took place. These included the selection of the decision criteria and their attributes, the decision structure and the utilty functions. The tasks of the decision panel should be expanded by including a discussion about the most appropriate decision criteria and the decision structure that should be used.

The panel should not only weight the criteria, they also have to determine the shape of the utility functions. This shape is an indication of the panel members' behaviour towards risk concerning the criterion involved. Target attribute values for the criteria were used, depending on the criterion, as lower or upper bound of the utility function. These also have an impact on the function's shape and thus need to be discussed by the panel members.

This work did not consider social metrics in the evaluation of the sustainability of a design alternative. Since sustainability also has a social dimension, future work needs to include appropriate metrics in order to reflect social changes that a large retrofit design project may bring about.

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APPENDIX A

SCIENTIFIC JOURNAL PAPERS

A.1 Techno-economic considerations for DIP production increase and implementation of cogeneration at an integrated newsprint mill

Techno-economic considerations for DIP production increase and implementation of cogeneration at an integrated newsprint mill

BY M. JANSSEN, F. CORNEJO, K. RIEMER, H.-C. LAVALLÉE, P.R. STUART

Abstract: The implementation of increased deinked pulp (DIP) production and cogeneration were considered at a hypothetical integrated newsprint mill. Pre-feasibility engineering estimates were completed, including an economic analysis. Next, risk analysis using Monte Carlo simulation was included in this analysis. It was shown that valuable information for decision making is revealed, like the probability of a design option not being profitable. The most attractive option was the 100% 1-loop DIP plant option with increased capacity to burn wood waste by conversion of a natural gas boiler.

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CONVENTIONAL PRE-FEASIBILITY DESIGN studies in the pulp and paper industry, either for greenfield or retrofit projects, involve methodologies that can result in a limited number of process design options being taken into account for further economic analysis. The cost estimates for the process design options under study are typically based on the knowledge and expertise of the engineering team, including risk analysis considerations related to future economic scenarios.

"Large-block" analysis involves a more systematic search of possible process design options than is typically undertaken, and complements the expertise of the engineering team. A large-block analysis is based on the representation of different process systems by the overall mass and energy balances of these process systems. This approach results in a larger number of process design options being explored as candidates for more detailed engineering.

Integrated newsprint mill energy considerations

Newsprint production requires large amounts of electricity and steam. Steam is typically generated by burning fossil fuel or biomass in the boiler house. Sludge from the effluent treatment plant can also be burned, but in the best cases, only at marginal energy recovery rates due to its high moisture content. The refiners in the TMP plant are the largest consumers of electricity mill-wide (typically > 2 MWh/bdmt). Heat recovery (i.e., recovery of generated steam from the TMP refiners) is an essential part of the TMP plant at most mills in order to increase the overall energy efficiency of the operation.

Although a number of techniques are available for reducing TMP energy consumption, they yield only marginal reductions when compared to the implementation of de-inked pulp (DIP) production to replace TMP (for a constant newsprint production rate). Such modifications have a dramatic effect on mill-wide energy consumption. By decreasing TMP production, the production of steam from the TMP plant (required principally for paper drying operations) is reduced. The mill must compensate for this loss of steam by increasing the steam production in the boiler house. Consequently, this increase can give rise to opportunities for changes in steam production, and potentially an enhanced opportunity for cogeneration at the mill. Cogeneration is the combined production of electrical (or mechanical) and useful thermal energy from the same primary energy source [1, 2].

Study objectives

The objectives of the present study are:

- To characterize a "base case" process design and process design options for the implementation of increased deinked pulp production and cogeneration system at an integrated newsprint mill,
- To analyze the economic feasibility of each option based on a large-block analysis,
- To further analyze the financial results based on risk analysis.

Although the problem definition and constraints are based on an operating integrated newsprint mill, adjustments have been made to create a hypothetical mill scenario. The design problem presented is an example of the approach a similar integrated mill could take in order to analyze DIP and cogeneration project options.

TECHNO-ECONOMIC STUDY

Methodology

The following methodology was used for the techno-economic study (Fig. 1):

1. A study was made of available and emerging technologies, an environmental review, and the gathering of necessary engineering data. Several DIP and cogeneration options were identified, and changes in the other mill processes as a result of the implementation of these options were evaluated using mass and energy balances.
2. These options were combined for the large-block analysis and their technological feasibility verified. For this purpose, an inventory of the inputs and outputs was constructed.
3. For each option, manufacturing and capital cost estimates were made. Based on these estimates, the NPV for each of the generated options was calculated.
4. The calculated NPVs were used to evaluate the feasibility of the options. All process options with a positive NPV were retained for further analysis.
5. A risk analysis was performed to assess the project risk for each process design option based on the uncertainty of certain manufacturing cost vari-

ables and financial parametres. Probability distribution functions (pdf's) were determined based on historical data to quantify this uncertainty. Monte Carlo simulation was used for incorporating the pdf's into the calculation of the NPV.

Assumptions and choices
Critical choices and assumptions that were made during the execution of this study are summarized in Table 1.

Base case configuration
The base case mill can be described by the following:

- Four newsprint machines have an average production of 1100 fmt/day,
- Two TMP lines that produce 925 admt/day,
- DIP plant that produces 175 admt/day,
- 70% of the wastepaper used is old newspaper (ONP) and 30% is old magazine paper (OMG),
- The activated sludge treatment plant treats approximately 50,000 m^3/day of wastewater,

The existing boiler plant produces approximately 7,000 GJ/day of steam.

Options for DIP and cogeneration plant
The options for the DIP and cogeneration plant were selected because they decreased overall mill energy costs. The techno-economic analysis methodology combined the reduced manufacturing costs and capital expenditures, by calculation of NPV. Other financial criteria are typically also considered, including total installed capital cost. In total, 18 options were analyzed in the large-block analysis by considering all combinations of the DIP and cogeneration possible. The combinations of six DIP and three cogeneration options were named according to the following method: Option {DIP Option 1, 2, ...6}-{Cogeneration Option A, B, or C}.

The DIP plant process design options considered in the study (summarized in Table II) considered increasing the DIP production to either 550 admt/day which represents 50% of the total pulp production, or to 1100 admt/day which is 100%. A 1-loop DIP configuration is the conventional technology used in North America. However, a 2-loop configuration can compensate for lower waste paper quality, expected in the coming years [1].

The cogeneration plant options considered the following (Table 3):

- Ability to increase biomass burning by the installation of hog fuel boilers,
- Reactivation of turbines to increase electrical output, and implementation of new back-pressure turbines.

Process block diagram for "large block" analysis
A process block diagram from a cogeneration perspective was developed for each of the 18 options as per Fig. 2. The energy consumption of the entire mill was calculated using this diagram, and the results were used in the calculation of manufacturing costs.

Cost modeling
Capital cost estimates
It is generally recognized that the precision of cost estimates falls within bounds which satisfy different purposes (e.g., project screening, project appropriation, construction, etc.). Since this evaluation was developed to screen multiple design options and system configurations, it employed an order-of-magnitude/pre-feasibility engineering precision (i.e., that required to evaluate and compare the costs and economic benefits). Any decision to proceed would require further estimate/analysis work to be done. The esti-

TABLE I. Design study assumptions.

Assumptions
Implemented technologies meet environmental regulations
Boilers have a net thermal efficiency of 75%
No extra electricity generated by using condensing turbines
Total investment is completed at time t = 0 and financial parametres are constant over the project lifetime
Choices
Market considerations are not taken into account[1]
Incremental de-bottlenecking is not considered[2]
Fluidized bed boilers are not considered[3]

[1] New process design options are compared with a base case
[2] This would render the problem at hand too complex
[3] Dryness of the hog fuel is high enough to use convention boilers

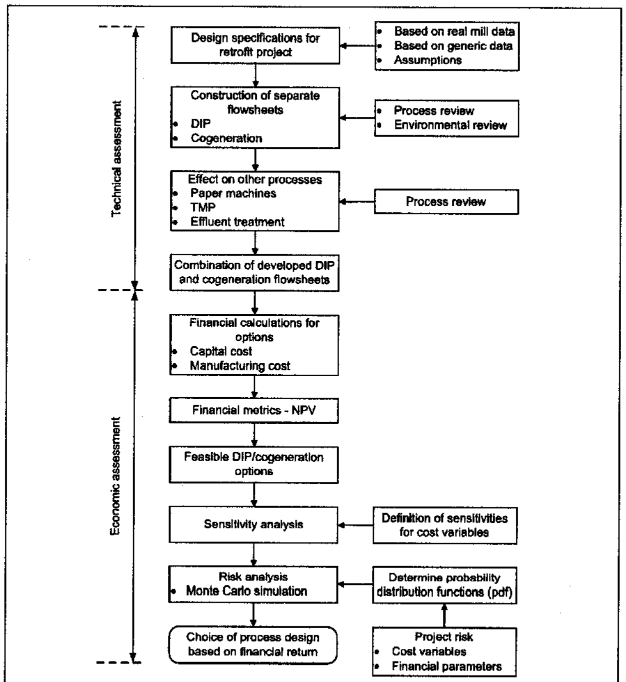

FIG. 1. Techno-Economic Study Methodology.

TABLE II. Configuration of the DIP plant options.

Option	Configuration
1	New 550 admt/day DIP plant, 1-loop
2	New 550 admt/day DIP plant, 2-loop
3	New 1100 admt/day DIP plant, 1-loop
4	New 1100 admt/day DIP plant, 2-loop
5	Increase DIP to 550 admt/day by adding a second line to the existing DIP plant, 1-loop
6	Increase DIP to 550 admt/day by adding a second line to the existing DIP plant, 2-loop

TABLE III. Configuration of the cogeneration options.

Option	Configuration
A	One natural gas boiler is converted to burn wood waste, and existing turbo-generators kept in service.
B	New wood waste boiler is installed. Half the boilers are upgraded to higher pressure operation. New turbo-generator added to existing ones.
C	New air-cooled condenser and turbo-generator are installed.

mates for both the DIP and cogeneration configurations were derived from a variety of sources including similar estimates. Cost ratios were employed to suit new production capacities, year of construction, etc.

For the capital cost estimate of the DIP system, an allowance for modifications of the paper machines was included to allow for the effects of using larger proportions of DIP in newsprint. Also, a contingency cost of 10% was included. This contingency cost compensated for the items not directly included in the capital cost estimate and was an approximation for the costs about which there was no information. No changes to the effluent treatment plant were anticipated under any of the new scenarios.

Manufacturing cost estimates

For each combined option, the manufacturing cost per finished metric tonne of newspaper was computed using the following cost items:

- Purchased electricity,
- ONP and OMG,
- Wood chips,
- Process chemicals,
- Natural gas,
- Hog fuel,
- Labour and staff.

Costs that remained constant for all options were not considered, since a comparison was being made to the base case design (e.g., newsprint transportation costs did not change between options since it was assumed that the end product and customer base were constant).

The manufacturing costs varied with the process design option. The differences in the cost of fibre and the cost of purchased electricity had the biggest impact on the overall manufacturing cost for each option. The cost of purchased electricity was clearly reduced in all the analyzed options when compared to the base case. This reduction depended on:

- The increased use of cogeneration at the mill,
- The amount of sludge generated by the DIP and effluent treatment plant,
- The amount of available hog fuel,
- The amount of TMP pulp produced, and
- The amount of steam regenerated in the Heat Recovery Unit (HRU) of the TMP plant.

The cost of fibre (ONP, OMG, and virgin fibre) was higher for all options compared to the base case, because the cost of ONP and OMG was higher than the cost of chips for producing TMP. The cost of chemicals also increased for each option when compared to the base case, since the use of chemicals per tonne of DIP pulp produced was higher than would be required in a TMP plant. The cost of labour varied mainly because of the amount of man hours used for ash landfill and sludge handling. The cost of staff was reduced in the 100% DIP options only, since in these options staff was no longer necessary for the TMP

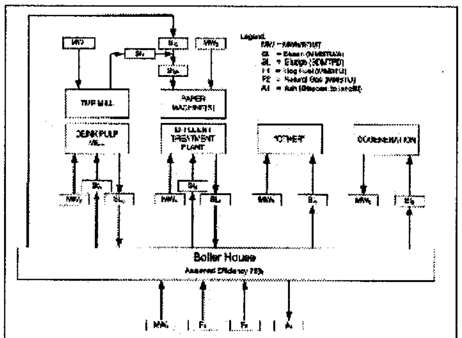

FIG. 2. Process block flow diagram of newsprint mill.

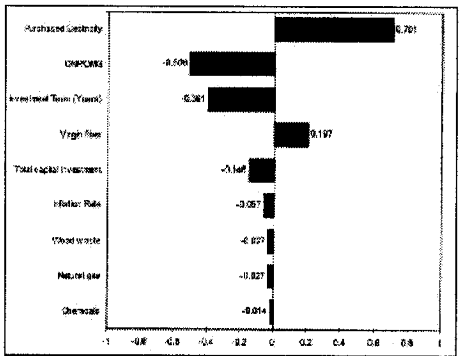

FIG. 3a. Tornado graph: Option 1-A.

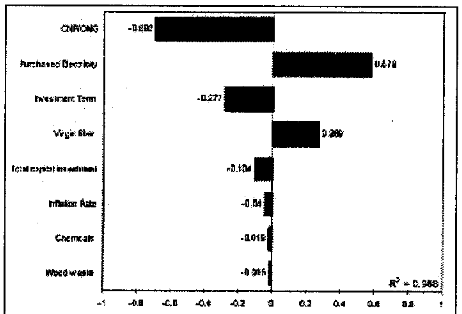

FIG. 3b. Tornado graph: Option 3-A.

TABLE IV. NPV for the ecoomically feasible process design options.

Option[1]	NPV (million $ CDN)
1-A	15.4
3-A	40.4
5-A	23.5
3-B	6.1

[1] See Tables 2 and 3 for design option descriptions

TABLE VI. Scenario analysis for 2-loop systems.

Scenario	Cost change	
	Electricity	Fibre
I	50%	10%
II	50%	50%
III	200%	0%

plant. The manufacturing costs for the options with a 2-loop configuration were all higher than the corresponding 1-loop design options. This was caused by:

- Higher electricity costs: 2-loop system has a higher specific energy (650 vs. 450 kWh/ tonne DIP),
- Higher fibre costs: the yield of the 2-loop system is lower (85% vs. 92% for the 1-loop system),
- Higher chemical costs: more chemicals are used in a 2-loop system than in a 1-loop system.

The natural gas cost varied per option based on the amount of sludge that was generated in-process. For cogeneration configurations A and B, the natural gas cost was lower for the 2-loop options than for the 1-loop options, because the former systems produced more sludge.

Recommendations from the large block analysis

The manufacturing cost and the capital cost were used as the basis for the calculation of the NPV for each of the process design options to determine their economic feasibility. The NPV was used as a screening tool to select options that had a positive NPV after 20 years. According to this criterion, four economically viable process options were retained: 1-A, 3-A, 5-A, and 3-B (Table IV). Option 3-A, a 1-loop DIP configuration, had the highest return after 20 years (40.4 M$).

It should be noted that none of the options with a 2-loop DIP system had a positive NPV after 20 years. The reason for this negative outcome is that these options incur higher manufacturing costs and require a higher capital investment for implementation than those with a 1-loop system. However, due to the projected decrease in waste paper quality over time, DIP plants may need to be upgraded to a 2-loop system, which is a more rigorous recycling technology.

RISK ANALYSIS

Analysis of retained design options

Risk analysis is the analysis of risks associated with the values of key project variables and parametres, and therefore associated with the overall project result. Quantitative risk analysis considers the range of probable values for key variables and parametres and defines a probability distribution function (pdf) for describing these uncertain variables and parametres. Combination of these pdf's may lead to an overall probability indicating that the project is unacceptable. A Monte Carlo simulation can be used to obtain this overall probability. A Monte Carlo simulation is a method that uses a pseudo-random generator for sampling to approximate a probability distribution. When deciding on a particular project or a portfolio of projects, decision-makers should take into account not only the expected value of the

TABLE V. Results from the Monte Carlo simulation for the retained options.

Option	Mean [10^6 $CDN]	P (NPV ≤ 0) [%]
1-A	20.4	20.3
3-A	44.9	16.4
5-A	28.2	12.0
3-B	10.9	41.4

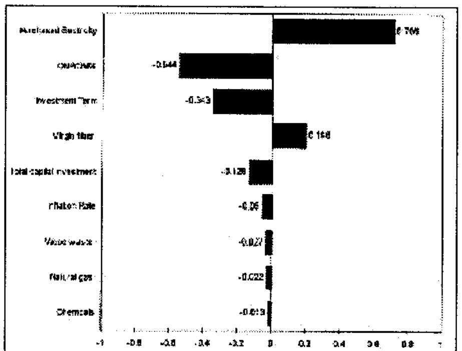

FIG. 3c. Tornado graph: Option 5-A.

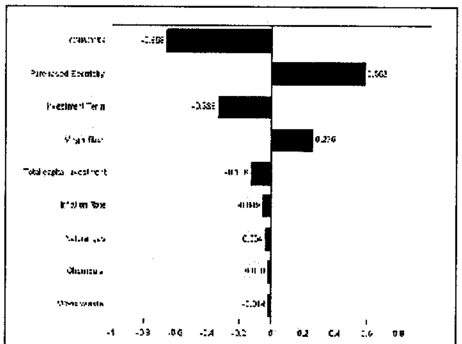

FIG. 3d. Tornado graph: Option 3-B.

NPV, but also the risk that the project's NPV will be negative. Therefore, a risk analysis using Monte Carlo simulation was carried out for the 4 options with a positive NPV.

First, the probability distribution functions (pdf's) for the price changes over time (volatility) were determined for the different variables and parametres based on data from Statistics Canada [4]. These variables and parametres included the inflation rate, as well as the cost of virgin and recycled fibre, electricity, chemicals, wood waste, and natural gas. Data from the time period 1993-2003 were used. It was assumed that the distributions for labour and staff costs had the same characteristics as the pdf for the inflation rate. For the investment term, a triangular distribution with a median of 10 years, a minimum of five years, a maximum of 15 years was assumed and for the total capital investment, a triangular distribution with a median of 0%, a minimum of -25% and a maximum of +25% was assumed. Also, it was assumed that the interest on capital, the cor-

TABLE VII. Results from the Monte Carlo simulation for the 3 best options under scenarios I, II and III.

	Option	Mean [10^6 \$CDN]	P(NPV ≤ 0) [%]
Scenario I	2-A	60.4	2.35
	4-A	70.7	11.0
	6-A	69.7	1.18
Scenario II	2-A	46.9	9.26
	4-A	39.6	27.2
	6-A	56.3	5.54
Scenario III	4-A	170.4	0.50
	6-A	142.0	0.00
	4-B	151.1	0.83

porate tax rate, the risk premium, and the debt to equity ratio remained constant over the project's lifetime. Then, the Monte Carlo simulation was executed using $1{\cdot}10^4$ iterations to obtain credible results (Table V).

Although option 3-A still had the highest average NPV (\$44.9 million CDN), the risk of obtaining a negative NPV (16.4%) was higher than that for option 5-A (12.0%), which had an average NPV of 28.2 million dollars (2nd highest). There is a trade-off between the value of the NPV and the risk to reach that NPV. This indicates that there are some drawbacks in considering the NPV as the sole measure of profitability for an investment, and that possibly other indicators should be used as well.

Using the Monte Carlo simulation, tornado graphs were generated (Fig. 3), depicting the simultaneous sensitivity of the NPV towards the different parametres and variables that were taken into account in the simulation. As such, the tornado graphs represent a more realistic view of the sensitivity of the NPV, since the variables and parametres are taken into consideration simultaneously instead of one-by-one.

The tornado graphs show that the cost of purchased electricity and recycled fibre had the highest impact on the NPV. They indicate that when the mill is transformed to a 100% DIP mill (options 3-A and 3-B), the recycled fibre cost has the highest (negative) impact on the NPV. Furthermore, they show that the cost of purchased electricity and the cost of virgin fibre have a positive impact on the outcome of the NPV in all cases.

In the risk and risk sensitivity analysis, the investment term and the total capital invested were also taken into account. While both have a significant impact on the NPV, they were not as critical as electricity and recycled fibre prices.

Two-loop systems

Scenarios were run in order to investigate the effect of changes in the price of recycled fibre and electricity on the financial return of the 2-loop DIP system (Table VI), to determine the conditions under which a 2-loop system would become profitable. These particular cost changes were selected because fibre and electricity prices are expected to increase in the future, and because these costs had the greatest impact on the NPV. The same pdf's used previously were assumed for parametres other than electricity and fibre costs.

An increase in the price of electricity had a positive effect on the resulting NPV of the options. Still, the risk of the investment also needs to be taken into account by examining P(NPV ≤ 0) (Table VII). Clearly, option 6-A would be the best design to choose for scenarios I and II, since it has the lowest risk and a near maximum or a maximum NPV, respectively. In the case of a doubling of the electricity price, P(NPV ≤ 0) even reached zero for option 6-A. Although option 4-A (highest NPV) had a higher risk, this risk was so small that this would be the preferred option under scenario III. This shows that the increase in the electricity price may influence the choice of the preferred process design option.

An increase in the price of fibre had a negative effect on the NPV of the options, as shown in scenario II (when comparing with scenario I). For each of these options, the average NPV decreased and the risk increased (Table VII). It is also clear that the increase in the cost of electricity had a larger impact on the NPV than the increase in the cost of recycled fibre (results not shown).

These results imply that deregulation of the electricity market, which is expected to lead to an increase in prices, may result in the implementation of more 2-loop de-ink systems in Canada, since with such an increase, the profitability of 2-loop systems increases. If these modifications were to be made, measures to minimize the cost of fibre would have to be taken, such as increasing the efficiency of the process. Furthermore, since a 2-loop system requires a higher capital expenditure, the necessary capital would have to be available for investment.

CONCLUSIONS

In this study, the implementation of increased deink pulp production and cogeneration was considered at a hypothetical integrated newsprint mill.

The capital and manufacturing costs were calculated by considering the effect the implementation of different process options would have on the rest of the mill. The process options with the 2-loop DIP technology were generally negative because of higher capital and manufacturing costs compared to the corresponding 1-loop DIP options.

A risk analysis demonstrated that the risk of a negative NPV can be taken into account in selecting a process option, and that the inclusion of uncertainty in the analysis of process options may reveal valuable information for decision making. The risk analysis showed that with increasing electricity and recycled fibre prices, the 2-loop DIP technology options may become profitable.

ACKNOWLEDGEMENTS

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Résumé: L'augmentation de la production de pâte désencrée et de la cogénération a été évaluée à une usine intégrée de papier journal hypothétique. Des études de préfaisabilité technique ont été effectuées, suivies d'une analyse économique. L'étude a indiqué que la technologie de désencrage en deux boucles n'était pas en général intéressante du point de vue économique. L'analyse des risques a démontré que des prix substantiellement plus élevés rendaient plus intéressante la technologie de désencrage en deux boucles du point de vue économique. La moindre qualité probable des approvisionnements de vieux papiers et l'augmentation probable des coûts de l'énergie pourrait éventuellement faire en sorte qu'on passe à des systèmes de désencrage en deux boucles en Amérique du Nord.

Reference: M. JANSSEN, F. CORNEJO, K. RIEMER, H.-C. LAVALLÉE, P.R. STUART. Techno-economic considerations for dip production increase and implementation of cogeneration at an integrated newsprint mill. *Pulp & Paper Canada* 107(9) T:184-188 (September, 2006) Paper presented at the 91st Annual Meeting in Montreal, QC, Canada, February 7-10, 2005. Not to be reproduced without permission of PAPTAC. Manuscript received January 05, 2005. Date of revised manuscript approved for publication by the Review Panel not available.

Keywords: RECLAIMED FIBRES, COGENERATION, NEWSPRINT MILLS, DEINKING, ENERGY CONSUMPTION, WASTE PAPERS, COST ANALYSIS

A.2 Development of an operations-driven cost model for continuous processes – Part II: Retrofit process design application

DEVELOPMENT OF AN OPERATIONS-DRIVEN COST MODEL FOR CONTINUOUS PROCESSES
PART II: RETROFIT PROCESS DESIGN APPLICATION

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Abstract: This paper presents a methodology for design decision making based on a cost accounting model that incorporates the principles of Activity Based Costing (ABC). The proposed approach provides an operations-driven view of manufacturing costs for mill processes, including both direct costs and overheads. This operations-driven view allows focusing on the mill processes themselves, whereas more traditional costing approaches focus on the product. The operations-driven cost modeling approach significantly increases the granularity and transparency of results from a techno-economic study, and permits the examination of critical design variables and operating variants. A case study is used to demonstrate this approach, by evaluating several retrofit process design alternatives for increased deinked pulp (DIP) production and cogeneration at an integrated newsprint mill.

Application: The cost model is used to evaluate retrofit design alternatives for an integrated newsprint mill, and helps to identify production policies that optimize the profitability of these alternatives by looking at energy-related design variables and parameters.

INTRODUCTION

Retrofit process design in the pulp and paper industry

Due in large part to market pressures in recent years, capital spending levels relative to depreciation have decreased dramatically in the pulp and paper industry. Companies thus seek methodologies to better evaluate capital spending opportunities that potentially improve mill processes and operational strategies. Manufacturing costs for retrofit design alternatives can be compared to current manufacturing costs using the mill process and cost data in financial spreadsheet models, and the resulting NPVs for the alternatives calculated. Furthermore, more advanced analysis such as Monte Carlo risk analysis can be carried out to assess risks associated with key project variables and parameters [1, 2]. One of the opportunities stemming from the effective use of data coming from Information Management Systems (IMS) at pulp and paper mills lies within the field of retrofit process design. By using more detailed and better structured models, analysis tools, methodologies, and data, better decisions can be made regarding the selection of the best design alternative for investment [3].

Cost modeling for retrofit process design

Classical techno-economic studies typically use volume-based cost accounting data as the basis for modeling costs. These studies yield good information for decision making for many design objectives, however can lack in granularity (detail) and transparency to permit a more careful evaluation of design alternatives when this is required.

Activity Based Costing (ABC) is a cost accounting method that increases both the transparency and the granularity of a cost model when compared to a volume-based cost model. This is due to the process-based nature of ABC and ABC-like models. By using the principles of ABC, cost accounting data can be systematically used for such applications as tracking production costs and cost variances in order to reduce variability in production and quality [4], and the evaluation of retrofit design alternatives where process and cost data are systematically reconciled. When a mill has an ABC-like system in place,

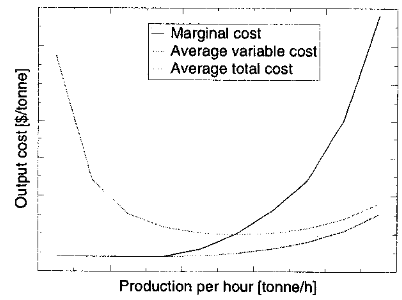


Figure 1: Illustration of marginal cost analysis

opportunities for more advanced and sophisticated analysis can be exploited, such as decision making for capital spending through sensitivity analysis, incremental and marginal cost analysis, or risk analysis. The first paper in this series includes a more in-depth discussion of ABC [5].

Marginal energy costing

In marginal economics, both incremental manufacturing costs and revenues are seen as variable. This results in a more realistic view of how costs per unit produced change, and may lead to the observation that unit manufacturing costs decrease at first, but then at some level start to rise as production increases (Figure 1). There is an optimum for capacity utilization [6]. Marginal cost analysis identifies operating scenarios that maximize the cash flow for a given investment and for different operating conditions. Furthermore, the use of production functions to characterize the (non-linear) resource behaviour of the operations allows for a more accurate view of manufacturing costs [7]. Therefore, marginal energy cost analysis helps identifying operating conditions at which maximum profitability can be achieved.

Integrated newsprint mill energy considerations

Although a number of techniques are available for reducing TMP energy consumption, they generally yield only marginal reductions when compared to the implementation of de-inked pulp (DIP) production to replace TMP (assuming a constant production rate). However, by decreasing TMP production, the production of steam from the TMP plant (used principally for paper drying operations) is reduced. The mill must compensate for this loss of steam by increasing steam production in the boilers. Consequently, this increase can give rise to further capital spending requirements, leading to consideration of cogeneration at the mill. Cogeneration is the combined production of electrical (or mechanical) and thermal energy from the same primary energy source [8]. Energy efficiency studies may be carried out to optimize the profitability of a design alternative by, for example, reducing steam demand in the process. Pinch analysis can be used for thermal optimization and for definition and organization of energy efficiency projects by reducing both energy and water use at a mill [9,10,11].

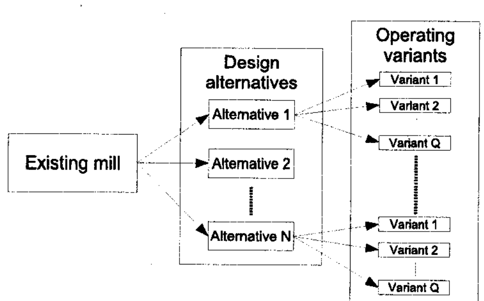


Figure 2: Development of process variants for design decision making

OBJECTIVES

This paper seeks to demonstrate the use and application of the operations-driven cost modeling approach [5] to a retrofit design problem using the data and structure of an ABC-like cost accounting system. The objectives of this study were as follows:

- To demonstrate the value of the operations-driven cost modeling approach in the evaluation of the design alternatives for design decision making
- To use the cost model to obtain insight into the design alternatives by considering operating variants (Figure 2) based on energy efficiency studies and analysis of production capacity change
- To identify the benefits of using this approach when compared to a rigorous but "classical" techno-economic analysis.

The case study considers the implementation of increased DIP pulp production and cogeneration at an existing integrated newsprint mill [1].

EXISTING MILL AND DESIGN ALTERNATIVES

Existing mill configuration

The existing mill on which this study is based consists of the following production units:

- 4 newsprint machines with a total average production of 1100 tonnes/day of newsprint,
- 2 TMP lines with a total average production of 925 tonnes/day of pulp
- A DIP plant with a total average production of 175 tonnes/day of pulp, where 85% of the wastepaper used is old newspaper (ONP) and 15% is old magazine paper (OMG).

Furthermore, the following supporting processes are part of the base case mill configuration:

- A wastewater treatment plant processing 50,000 m^3/day
- A boiler plant producing 7850 GJ/day of steam
- A back-pressure turbine generating only 0.4% of the total mill electricity demand.

De-inking and cogeneration design alternatives

The DIP plant process design configurations considered in the study would increase DIP production to either 550 tonnes/day (50%) or 1100 tonnes/day (100%) (Table 1). Both the 1-loop and 2-loop DIP technologies were considered. A 1-loop DIP system is a system that processes the recycled paper in one alkaline cleaning stage. A 2-loop system has an additional second cleaning loop that operates under acidic conditions making it a more rigorous cleaning process. The 1-loop de-inked plant configuration is the typical configuration used in North America, and its capital cost is lower when compared to a 2-loop system with the same capacity. However, a 2-loop configuration has additional equipment that compensates for expected quality loss of recycled paper in the future [12]. The cogeneration configurations had the following characteristics (Table 2 and Figure 3):

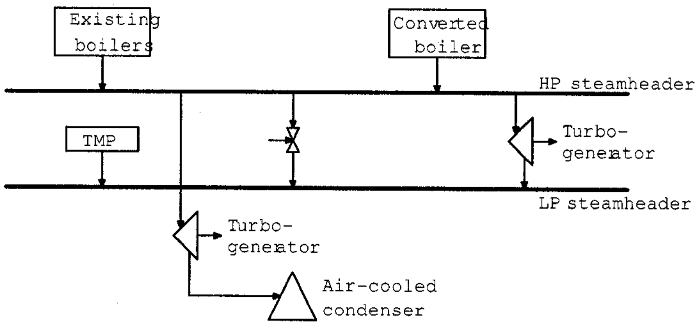
- Increase of biomass combustion capacity
- Reactivation of idled turbines, and implementation of new back-pressure turbines or condensing turbines.

Table 1: DIP plant configurations

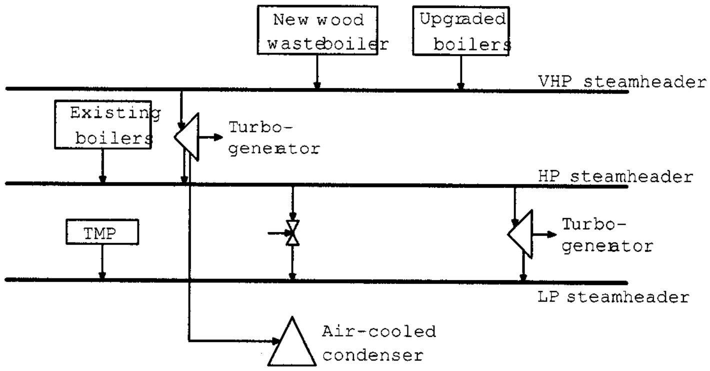
Option	Configuration
1	New 550 t/d DIP plant, 1-loop
2	New 550 t/d DIP plant, 2-loop
3	New 1100 t/d DIP plant, 1-loop
4	New 1100 t/d DIP plant, 2-loop
5	Increase to 550 t/d by adding a second line to the existing plant, 1-loop
6	Increase to 550 t/d by adding a second line to the existing plant, 2-loop

Table 2: Cogeneration configurations

Option	Configuration	Steam production
Existing mill	All boilers operate at high pressure (HP) and only one turbine is in service	At HP: 90,000 tonnes/year
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines kept in service.	At HP: 150,000 tonnes/year
B	New wood waste boiler (at very high pressure (VHP)) is installed. Three out of six boilers are upgraded to VHP operation. New backpressure turbine added.	At VHP: 130,000 tonnes/year At HP: 25,000 tonnes/year
C	New condensing turbine installed.	At HP: 100,000 tonnes/year



a.



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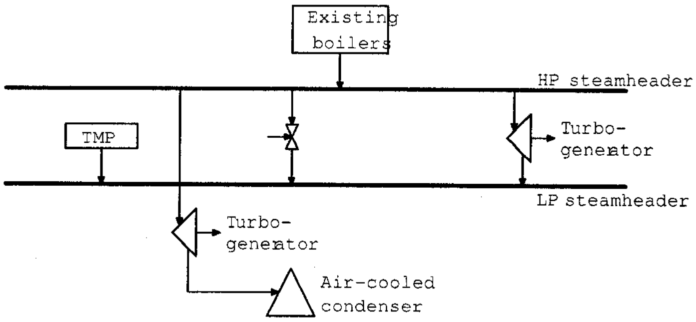


c.

Figure 3: Cogeneration options: a. option A, b. option B, and c. option C

In total, 18 alternatives were analyzed in this case study by considering all combinations of the 6 DIP and 3 cogeneration configurations. The following naming convention for the design alternatives was used: Alternative {DIP configuration 1 to 6 as per Table 1}-{Cogeneration configuration A, B, or C as per Table 2}.

METHODOLOGY

After developing the operations-driven cost model for existing mill processes, the study methodology consisted of the following steps for each of the design alternatives (Figure 4):

1. Calculation of mass and energy balances for each process flowsheet
2. Calculation of total capital costs
3. Modeling and calculation of operating costs for the design alternatives and process variants
4. Profitability calculations for the evaluation of the design alternatives and process variants.

These four steps are discussed in more detail next. The model was developed using the software package Impact: EDC™ from 3C Software Inc. [13].

Operations-driven cost model

Process data were used as inputs for the operations-driven cost model [5]. For the calculation of the variable costs, *Process Work Centres* (*PWC*s) were used to represent different mill processes. The *PWC*s were divided into production and support *PWC*s (Figure 5). The overhead costs were calculated in the *Overheads Work Centre* (*OWC*). The data used in this study provided detailed information about the indirect manufacturing cost per *PWC* and could therefore be directly related to the *PWC*s. Specifically allocated non-manufacturing costs were distributed equally over the *PWC*s in a second-level allocation. Some overhead costs varied per design alternative and operating variants, and were modeled in the *OWC*. For instance, due to changes in production volumes, the labour costs and headcount in the TMP and DIP *PWC*s varied. In the case study, the following *PWC*s had varying overhead costs: TMP, chip handling, DIP, turbines, and boilers.

Capital cost estimates & mass and energy balances

The total capital cost and the mass and energy balance models were constructed as described in Janssen *et al* [1]. The mass and energy balance model was used to examine the impact of varied steam generation in the boilers. Within this model, the cogenerated power was also calculated. The outcomes from the design options were directly connected to the operations-driven cost model.

Process design evaluation

Evaluation of design alternatives: Various profitability metrics were calculated to evaluate the feasibility of the design alternatives, including Net Present Value (NPV), Internal Rate of Return (IRR), Return On Investment (ROI) and cumulated Economic Value Added (EVA). EVA is an estimate of the wealth creation potential from capital investments. EVA attempts to capture the true economic profit of a company or project and accounts for the cost of capital [14]. Calculation of NPV is only based on cash flow, whereas EVA also takes into account the riskiness of an investment. Sensitivity analyses were carried out for the electricity and natural gas prices.

Marginal energy cost analysis: In this analysis, the marginal steam cost (in $/GJ) and the incremental and marginal cost of generated power (by cogeneration) (in $/MWh) were calculated. This was done by first varying the steam production in the steam plant over a range of values. Next, the total steam cost and turbine steam cost (i.e. cost of steam used by turbines for cogeneration) were calculated using the steam price:

$$\text{Total steam cost}_i = \text{Steam produced}_i \cdot \text{Steam price}_i \tag{1}$$

$$\text{Turbine steam cost}_i = \text{Turbine steam use}_i \cdot \text{Steam price}_i \tag{2}$$

The steam price was calculated based on the fuels used. By using difference equations, the marginal steam cost and marginal cost of generated power can be calculated as follows:

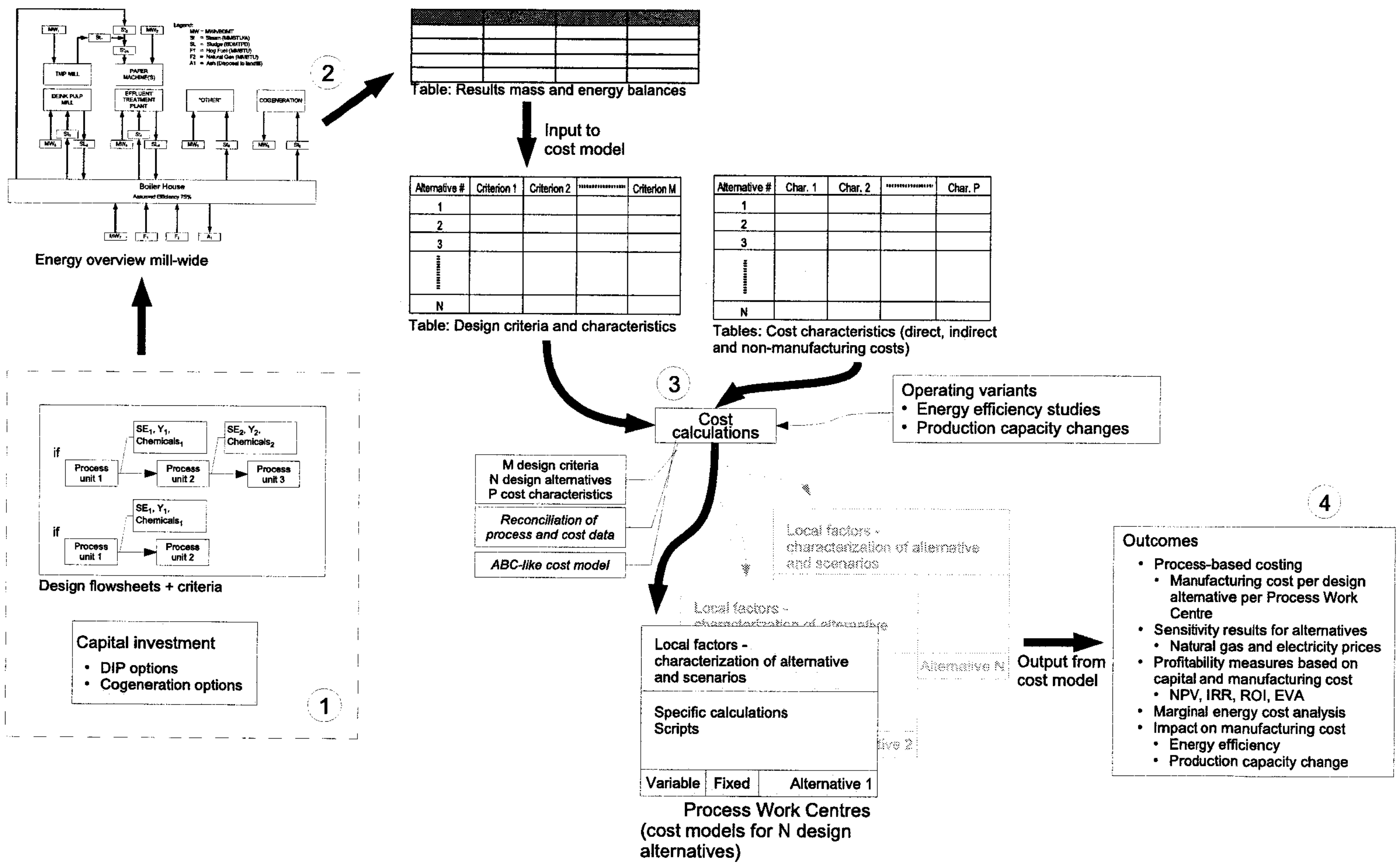


Figure 4: Operations-driven cost modeling approach

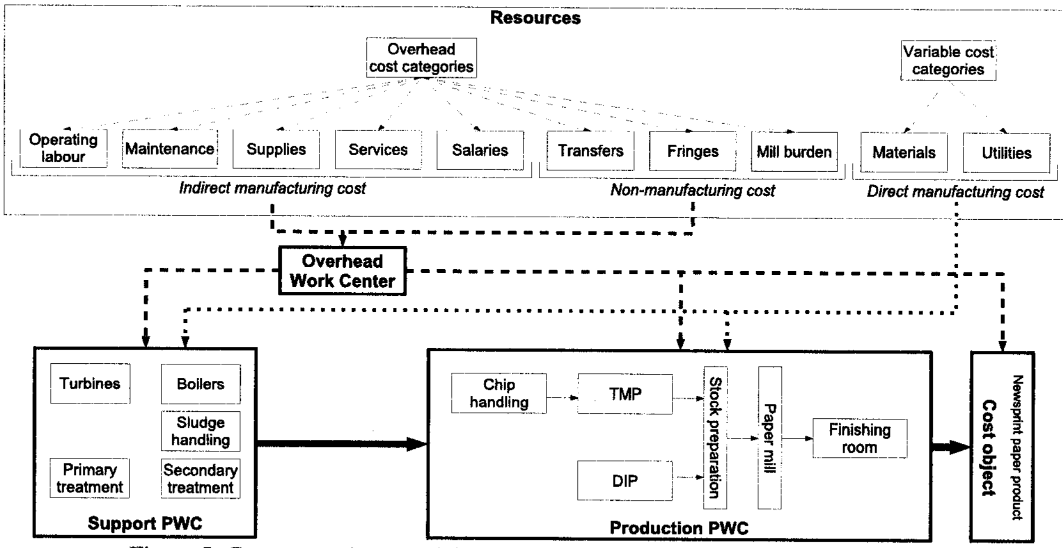


Figure 5: Cost categories and division of *PWCs* into production and support *PWCs*

$$\text{Marginal steam cost} = \frac{\text{Total steam cost}_i - \text{Total steam cost}_{i\text{-}1}}{\text{Steam produced}_i - \text{Steam produced}_{i\text{-}1}} \tag{3}$$

$$\text{Marginal cost of generated power} = \frac{\text{Turbine steam cost}_i - \text{Turbine steam cost}_{i\text{-}1}}{\text{Power generated}_i - \text{Power generated}_{i\text{-}1}} \tag{4}$$

where *i* refers to an operating variant.

The incremental cost of generated power of an alternative was calculated relative to the existing mill:

$$\text{Incremental cost of generated power} = \frac{\text{Turbine steam cost}_{\text{alt.}} - \text{Turbine steam cost}_{\text{exist.}}}{\text{Power generated}_{\text{alt.}} - \text{Power generated}_{\text{exist.}}} \tag{5}$$

where *alt.* refers to the considered retrofit design alternative.

Energy efficiency: The impact of increased energy efficiency of the process was considered in certain scenarios. This was done by reducing the steam use of the mill over a range of values of up to $6.45{\cdot}10^5$ GJ/y, corresponding to a maximum reduction of 20% for the 100% DIP alternatives and one of 25% for the 50% DIP alternatives, followed by calculation of the marginal steam cost, cost of generated power and profitability.

Production capacity change: Production functions were established to add non-linear resource behaviour resulting from a change in paper production. Functions for electricity and steam use of the paper machines were determined, using the following assumptions (Figures 6 and 7):

- Base load steam: 30% of nominal use
- Base load electricity: 70% of nominal use
- Steam use for drying decreases by 1% per 10 tons of production increase.

The base load refers to the amount of steam or electricity used by the paper machine when no paper is produced. Causes of non-linearity in the paper machines include the steam condenser efficiency and the efficiencies of paper machine drives and pumps.

Production functions for the efficiency of the cogeneration options were determined (Figure 8). Since no data were available for the separate boilers, these functions are composite functions describing all boilers in an option. Quadratic behaviour between the steam production and efficiency was assumed [15] with maximum efficiency being 75% for the base steam production. This non-linear behaviour may be caused by moisture levels in the fuel and air, incomplete combustion, combustion of hydrogen (to water), and radiation [16]. Linear behaviour was assumed for electricity use in the TMP plant with pulp production and for power generation in the turbines with steam production [16]. Furthermore, it was assumed that electricity use in the 100% DIP plants stays constant with changing deinked pulp production, because a constant volumetric rate is maintained.

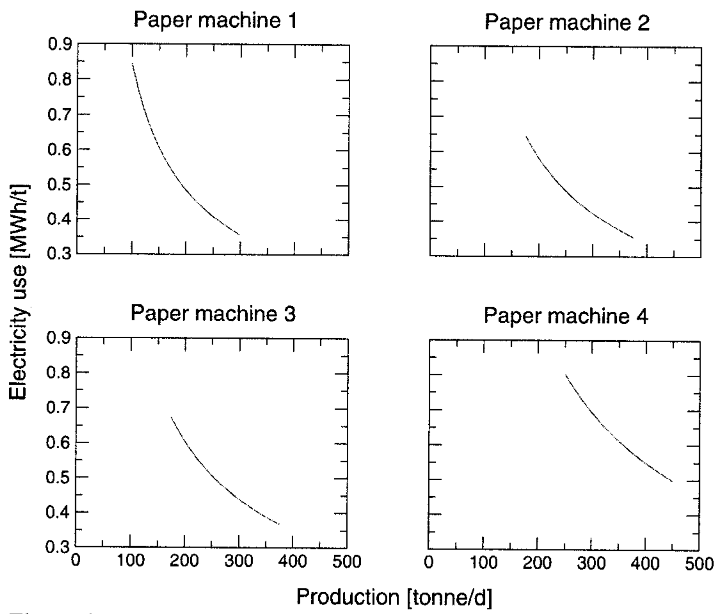


Figure 6: Production functions for electricity use in the paper machines

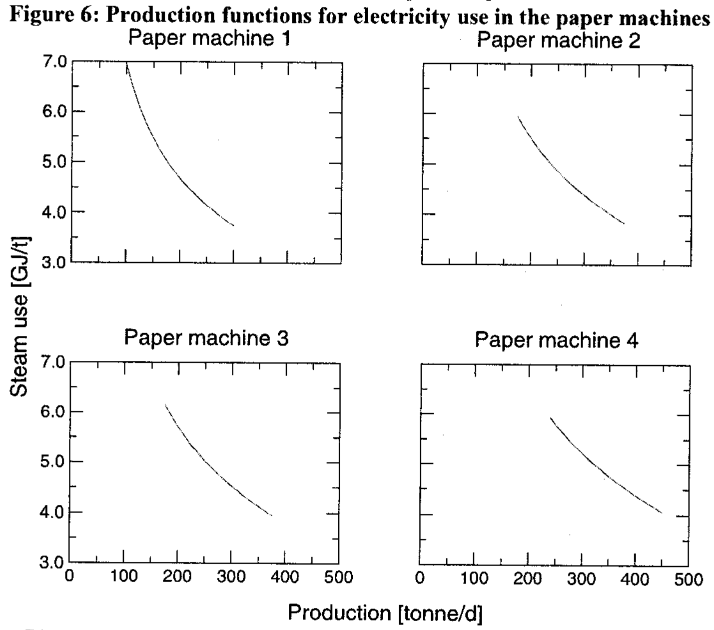


Figure 7: Production functions for steam use in the paper machines

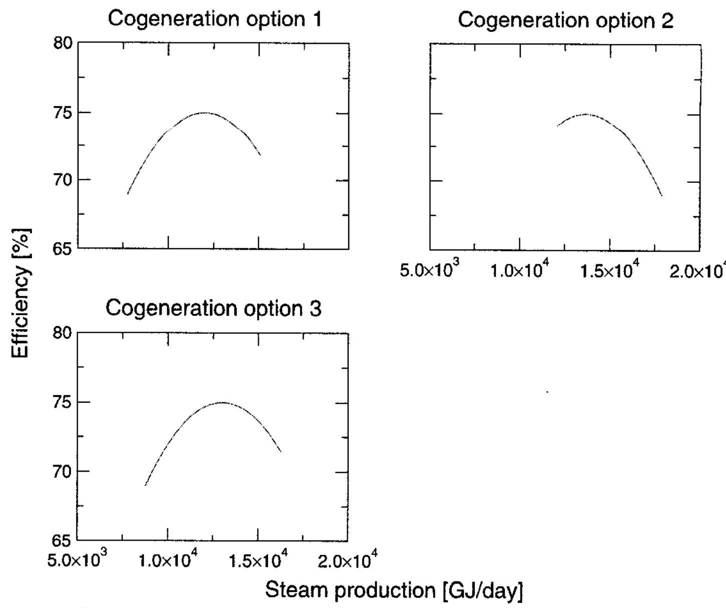


Figure 8: Efficiency functions for each cogeneration option

RESULTS & DISCUSSION

Manufacturing costs and profitability

The profitability of the design alternatives was performed under the following conditions:

- Declining balance method for depreciation with a fixed depreciation rate [17],
- Investment tax credit of $10/MWh of electricity generated based on renewable fuels [18],
- Generated electricity was sold to the grid at the nominal electricity price plus a 50% premium. This premium stimulates mills to sell their cogenerated power.

The manufacturing costs were split into direct and overhead cost and specified per *PWC* (Figure 9). A negative value for a *PWC* cost indicates that this *PWC* is a profit centre. For instance, for alternative 1-A, the manufacturing cost is (310 – 37) + (217 – 18) = 472 $/tonne. The turbine work centre is an important profit centre because of the sales of the generated electricity to the grid. Therefore, the turbine *PWC* direct cost for each alternative is negative. The cost of fibre is the most significant cost for the TMP and DIP *PWC*s, and depends on the implemented DIP option (50 or 100%) as well as the yield difference between the 1-loop and 2-loop configurations (85% vs. 92%). Furthermore, there is a difference in steam consumption: the 1-loop configuration uses 1.25 GJ/t and the 2-loop configuration 2.25 GJ/t of waste paper used. This is caused by the use of extra steam in the disperger for better pulp cleaning in the 2-loop configuration. The disperger utilizes steam and electrical energy to break down dirt and stickies remaining in the pulp for easier removal in the second loop. The variation in the direct cost for the paper mill *PWC* can be explained primarily by the variation in steam price, since the paper mill is a large steam consumer. The steam price depended on the wood waste capacity of the cogeneration options, and the amount of natural gas and sludge used for steam generation. One advantage of using the operations-driven cost modeling approach is that a higher manufacturing cost for the paper mill *PWC* can be clearly traced back to higher steam prices resulting from an increase in the cost of natural gas.

The overhead costs per alternative do not show a large variation compared to the direct costs (Figure 9). These variations occur because of:

- Differences in the Investment Tax Credit (ITC); the more power is generated based on renewable fuels, the more ITC is received

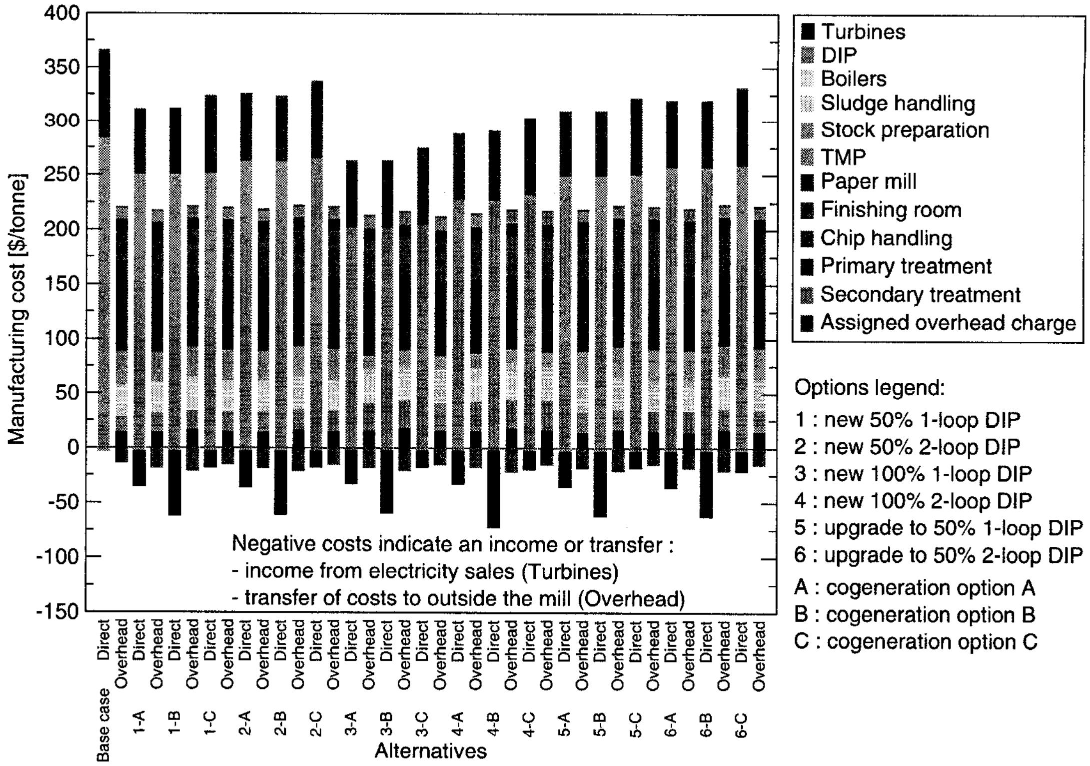


Figure 9: Manufacturing cost per tonne newsprint per design alternative and *PWC*

- Differences in maintenance material and labour, operating labour, and supply costs, and changes in headcount
- Differences in the cost of mill heating, which varies with steam price.

For each *PWC*, the "assigned overhead charge" is the non-manufacturing cost that was assigned directly to the cost object, the produced newsprint paper. This cost is negative because it contains costs that are transferred to other facilities at the mill site. Using the operations-driven costing approach, the *PWC*s that contribute to a manufacturing cost change can be identified. At a more detailed level, the change in cost per activity in these *PWC*s can be assessed.

Based on the results of the profitability analysis (Figure 10), the alternatives that had a positive value for all the criteria were retained and further analyzed. Alternative 3-A was most profitable with an NPV of 82.3 M$ and an IRR of 8.1%.

Sensitivity analyses were carried out to assess the impact of electricity and natural gas prices on the profitability of the design alternatives (results not shown). The natural gas and electricity consumption levels are lower for the design alternatives than for the existing mill, and therefore increased energy prices have a positive impact on the profitability. Both the electricity and the natural gas prices influence the steam price and incremental cost of generated power (eq. 5) (Figure 11). An electricity price change has a minor effect on both, even in the extreme case of a 100% change. However, an increase in the natural gas price results in a more significant change. The incremental cost of generated power can be reduced, change only a little, or increase depending on the steam price increase for the existing mill and the alternative.

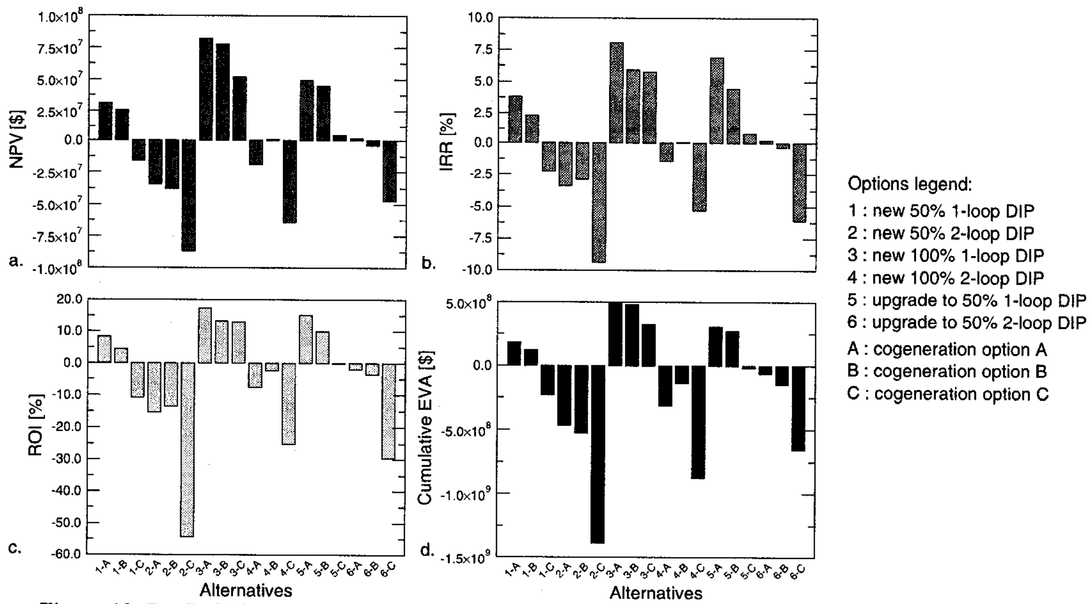


Figure 10: Profitability metrics for the design alternatives: a. NPV; b. IRR; c. ROI; d. cumulative EVA

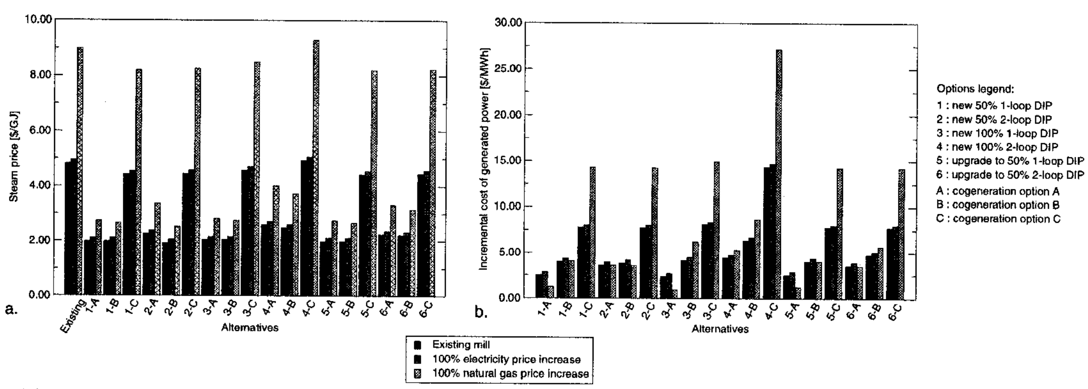
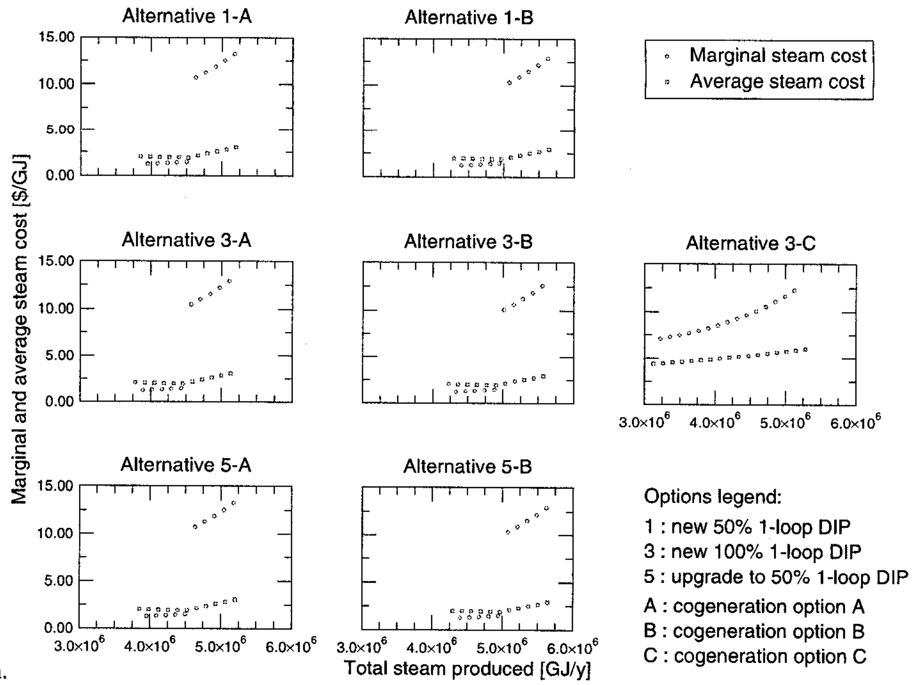


Figure 11: Effect of varying electricity and natural gas prices on: a. steam price, and b. incremental cost of generated power

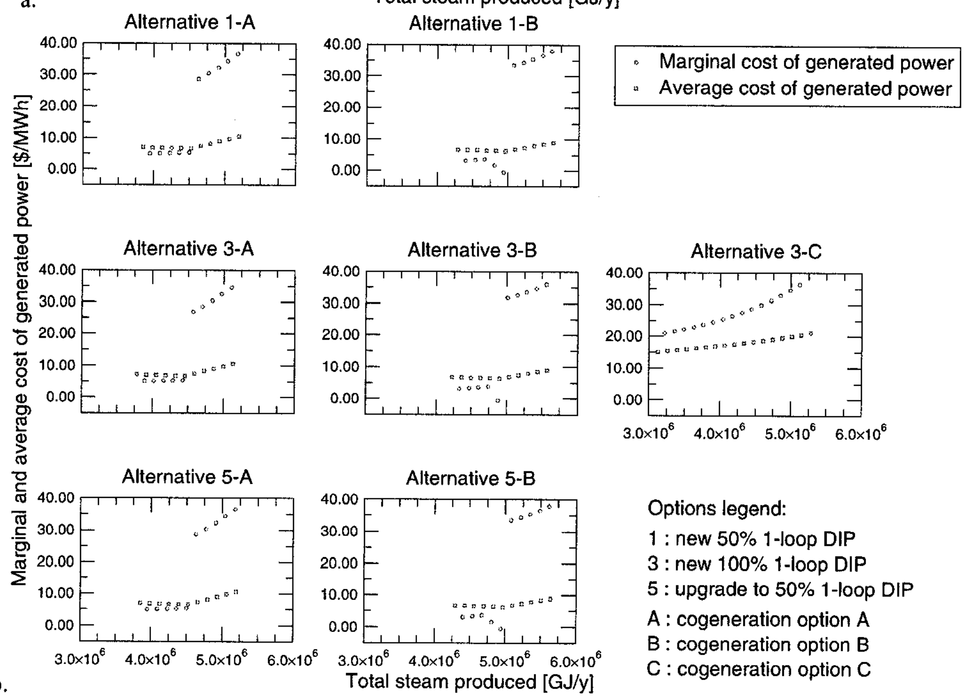
Marginal energy cost analysis

Figure 12a shows the impact of changing fuels on steam cost, by plotting marginal and average steam costs at different steam production rates. For alternatives with cogeneration options A and B, the marginal steam cost is lower than the average steam cost when steam production is from wood waste (lower steam production rates). After natural gas is added to the fuel mix, the marginal steam cost is significantly higher than the average steam cost. For instance, the average steam cost in alternative 3-A is \$2.15/GJ until natural gas is used, when the marginal cost jumps to \$10.50/GJ. Only alternative 3-C does not display a jump in the marginal steam cost, and has a marginal steam cost higher than the average steam cost at all steam production rates because of natural gas use at these rates. The marginal cost of generated power shows a similar trend (Figure 12b).

For the alternatives with cogeneration options A and B, an optimal NPV is identified as a function of variant parameters, specifically when wood waste use is maximized and natural gas use is minimized. These results reflect the outcomes of the marginal energy cost analyses, i.e. these alternatives would start to lose money as soon as natural gas is required (Figure 12c).


Alternative 1-A
Alternative 1-B
Marginal steam cost
Average steam cost
Alternative 3-A
Alternative 3-B
Alternative 3-C
Alternative 5-A
Alternative 5-B
Marginal and average steam cost [$/GJ]
15.00
10.00
5.00
0.00
3.0×10^6
4.0×10^6
5.0×10^6
6.0×10^6
Total steam produced [GJ/y]
Options legend:
1 : new 50% 1-loop DIP
3 : new 100% 1-loop DIP
5 : upgrade to 50% 1-loop DIP
A : cogeneration option A
B : cogeneration option B
C : cogeneration option C

a.


Alternative 1-A
Alternative 1-B
Marginal cost of generated power
Average cost of generated power
Alternative 3-A
Alternative 3-B
Alternative 3-C
Alternative 5-A
Alternative 5-B
Marginal and average cost of generated power [$/MWh]
40.00
30.00
20.00
10.00
0.00
3.0×10^6
4.0×10^6
5.0×10^6
6.0×10^6
Total steam produced [GJ/y]
Options legend:
1 : new 50% 1-loop DIP
3 : new 100% 1-loop DIP
5 : upgrade to 50% 1-loop DIP
A : cogeneration option A
B : cogeneration option B
C : cogeneration option C

b.

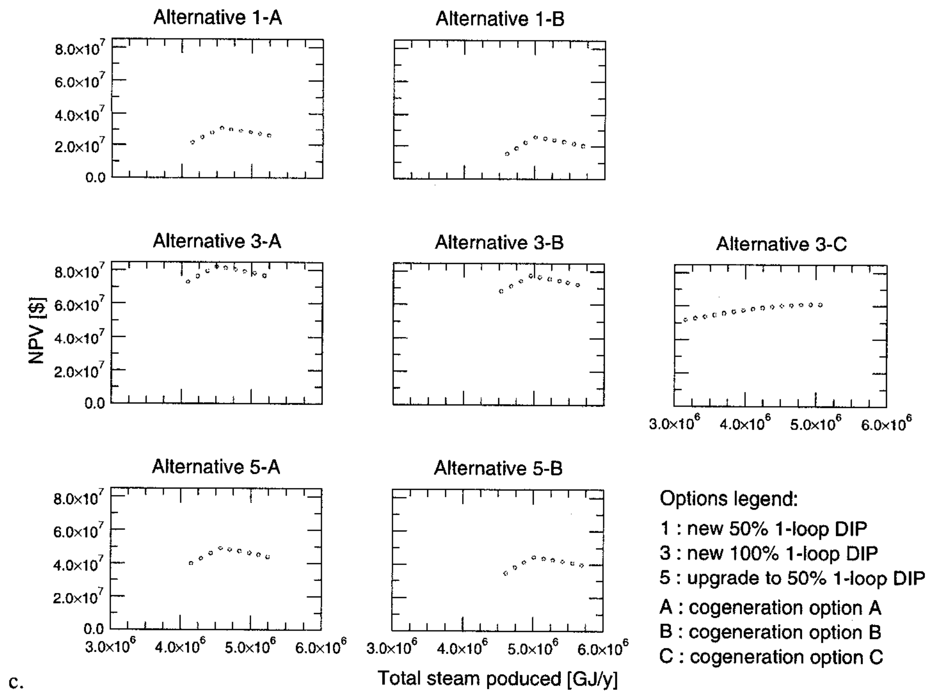


Figure 12: Marginal energy economics at constant process steam use: a. marginal steam cost; b. cost of generated power; c. NPV change

Energy efficiency

Increasing the energy efficiency of the process does not result in a significant impact on the marginal steam cost, nor on the incremental and marginal cost of generated power. However, the impact on the profitability is more profound (Figure 13). If the steam production in the boilers is decreased by the same quantity as is conserved by the higher energy efficiency, then the NPV decreases significantly. The decrease in steam production leads to lower electricity generation, and therefore the mill receives less revenue from the sales of this power. For instance, the NPV of alternative 3-A decreases from $82.3 million to $71.4 million when decreasing steam production in the boiler plant with 15%. The operations-driven approach is readily capable of quantifying such changes in profitability. If the steam production in the boilers remains at the base operating level, the NPV increases with decreasing process steam use. For greatest profitability, the cogeneration potential should remain as high as possible while maintaining an optimal fuel mix.

Production capacity change

The paper making process exhibits non-linear behaviour with regards to electricity and steam use by the paper machines and boiler efficiency. The manufacturing costs for varying production capacities have been calculated using the production functions (shown earlier in Figures 6, 7, and 8) and using constant values for those production variables. The calculations were carried out for design alternatives 3-A and 5-A. Using production functions leads to different manufacturing costs (Figure 14). This difference is amplified the further the production varies from the base design specification (in this case 1100 FMT/day for all paper machines). The overhead costs were not varied for these calculations.

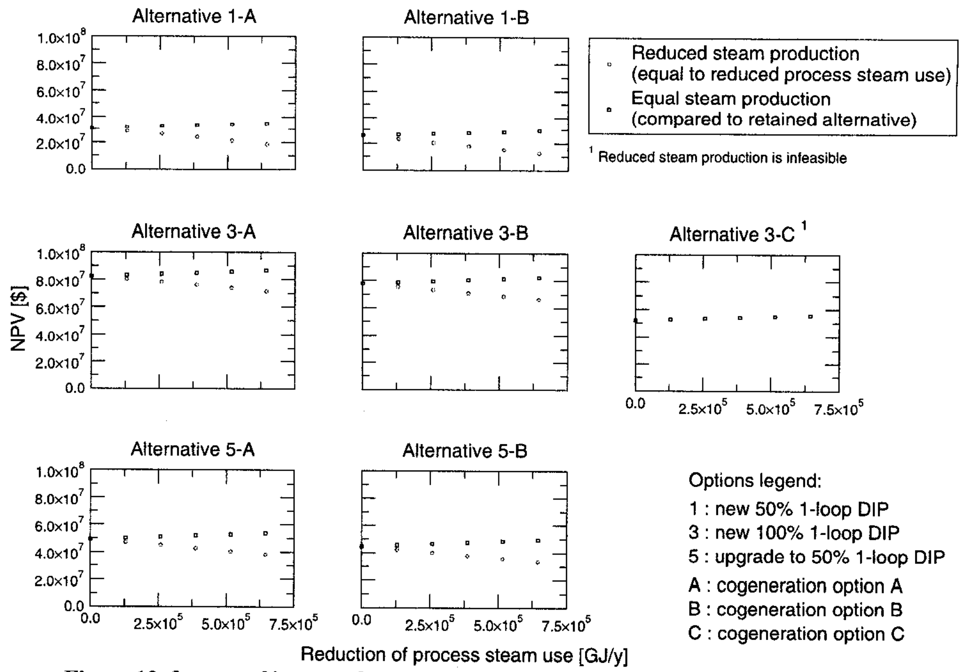


Figure 13: Impact of increased energy efficiency for the base alternatives on the NPV

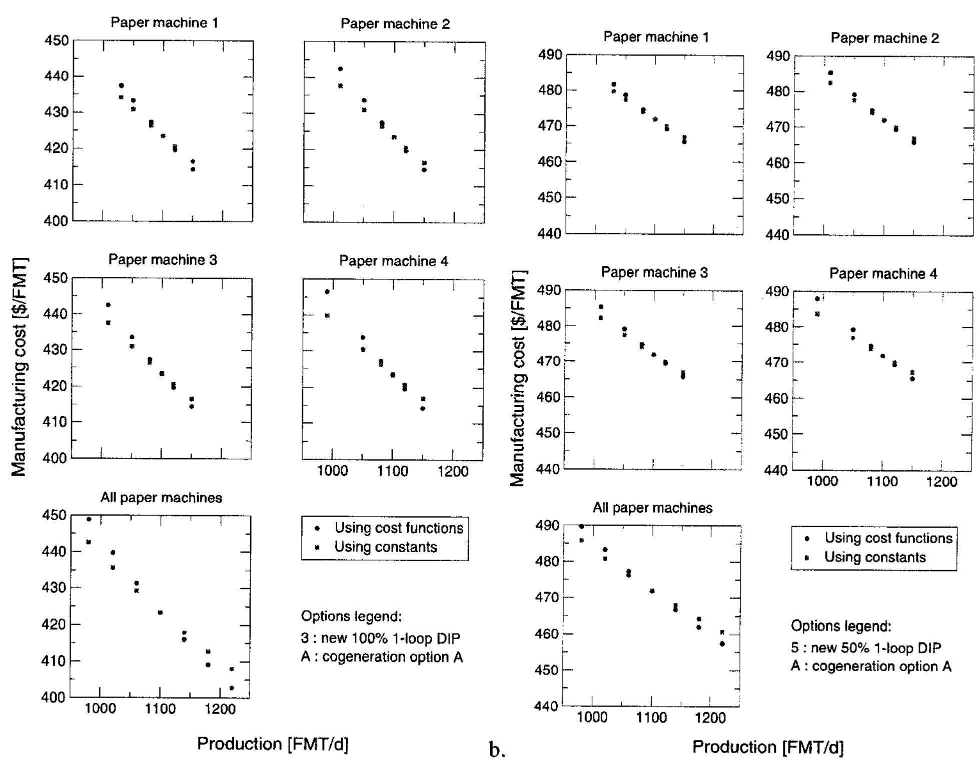
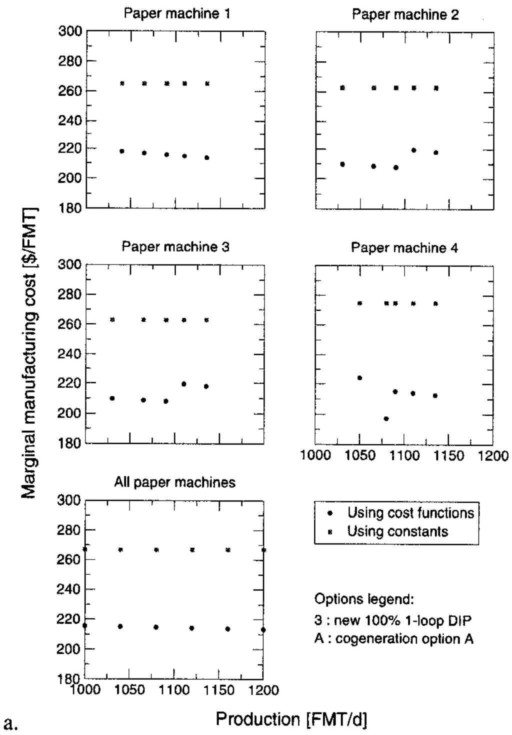


Figure 14: Manufacturing cost for: a. alternative 3-A; and b. alternative 5-A

The graphs entitled "All paper machines" show the manufacturing costs for simultaneous, equal variation in all the paper machines



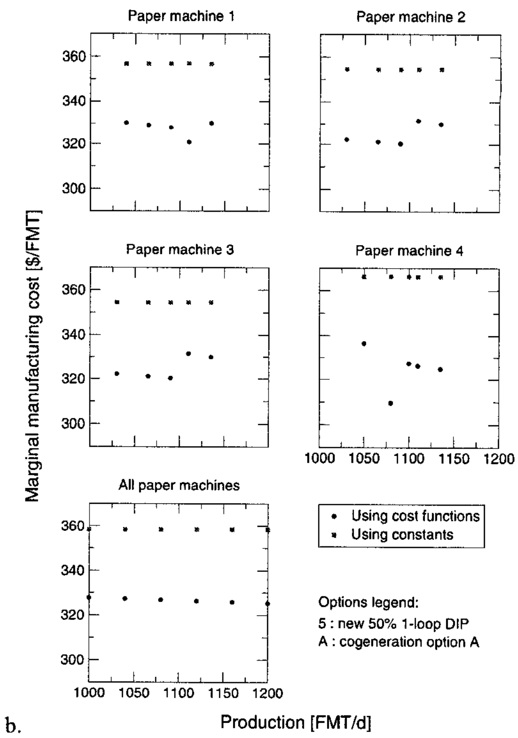


Figure 15: Marginal manufacturing cost for: a. alternative 3-A; and b. alternative 5-A
The graphs entitled "All paper machines" show the marginal manufacturing costs for simultaneous, equal variation in all the paper machines

The marginal manufacturing cost changed over the production range and resulted in a non-linear behaviour of the manufacturing cost (Figure 15) with production rate. This marginal cost was calculated using the following equations:

$$\text{Marginal manufacturing cost} = \frac{\text{Total manufacturing cost}_i - \text{Total manufacturing cost}_{i\text{-}1}}{\text{Production rate}_i - \text{Production rate}_{i\text{-}1}} \quad (6)$$

$$\text{Total manufacturing cost}_i = \text{Production rate}_i \cdot \text{Manufacturing cost}_i \quad (7)$$

where i refers to an operating variant.

The marginal manufacturing cost over the production range is higher for alternative 5-A. This implies that there is a significant impact of TMP operating costs (i.e. electricity use) on the marginal cost of the alternatives, because alternative 3-A produces no TMP pulp. For both alternatives, the marginal manufacturing costs stay well below the average manufacturing cost (Figure 14), which indicates that increased paper production leads to increased earnings for all production rates.

COMPARISON WITH CONVENTIONAL TECHNO-ECONOMIC APPROACH

Janssen *et al* [1] presented a techno-economic study for the same design problem as the one presented in this study. By comparing the operations-driven cost modeling approach used in this study with that of the classical accounting data used in the earlier techno-economic study, we find that:

- The transparency and granularity of the results increases because of the use of the ABC-like approach. The resources are related to the cost object through the activities performed in the defined *Process Work Centres*. In techno-economic studies, the resources are directly related to the cost object, i.e., the resource costs are paid for by the whole mill instead of by the process unit where the resource is used.

- The operations-driven approach allows for a detailed integration and reconciliation of the process and cost data in one model. The *PWCs* can be used to study a process at any level of detail depending on the objective of the study and the available and accurate data. This permits a more efficient and accurate description of changes in direct and overhead costs based on design changes. In a techno-economic study, the data are not captured in such a framework and it is therefore less obvious to link design changes to cost changes.
- The current approach integrates the calculation of design variables that change with resource price, e.g. steam price. The cost of resource use can be traced back to the *PWCs* that use these resources indirectly, e.g. changing steam cost for the paper mill *PWC* as a function of varying natural gas price. Such changes are not so obviously taken into account in a techno-economic study.

CONCLUSIONS & IMPLICATIONS

This study sought to apply an operations-driven cost modeling approach to a large-scale retrofit design problem. This problem considered the implementation of increased deinked pulp production and cogeneration at an integrated newsprint mill.

First, the mass and energy balances and capital costs were calculated for all design alternatives. Next, the operations-driven cost model was used to calculate the operating costs and profitability of the alternatives. The profitable alternatives were identified and marginal cost analyses and energy efficiency studies were carried out in order to further analyze these alternatives.

The profitability analysis showed that a 100% DIP 1-loop alternative was most profitable (alternative 3-A) and that none of the 2-loop DIP design alternatives were profitable. Marginal cost analysis quantified the negative effect of natural gas use on the alternatives' profitability due to its high price. Furthermore, an energy efficiency study showed that profitability only increases when maintaining steam production in the boiler plant while increasing energy efficiency of the mill processes.

The proposed cost modeling approach is better able to quantify cost implications of retrofit design changes due to its focus on the mill processes. The approach readily permits carrying out marginal cost analysis and energy efficiency studies because of its ability to calculate cost variations by evaluating operating variables such as the steam production rate.

ACKNOWLEDGEMENTS

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A.3 Supply chain level aspects of a methodology for sustainable retrofit process design

Supply chain level aspects of a methodology for sustainable retrofit process design

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Abstract

This paper presents a method for supply chain level analysis using supply chain and Life Cycle Assessment models, related to retrofit design decision making. The supply chain and LCA models use process and cost information that is provided by the an operations-driven cost model. Scenarios that reflect different market conditions have been defined to study the behaviour of the design alternatives from an economic and environmental perspective. The results of these analyses provide decision makers with information that may help them to make more sustainable design decisions. The results of a retrofit design case study are presented to demonstrate the capabilities of the proposed method.

Key words: Supply chain modeling, Life cycle assessment, Sustainability, Chemical process design, Decision making

1. Introduction

In recent years, sustainability has gained more and more attention. The Brundtland commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [1]. The concept of sustainable development consists of three dimensions: an economic, an environmental and a social dimension. In chemical process design, be it greenfield or retrofit, usually only the economic aspect has been considered explicitly as an objective and the environmental and social aspects have been used as constraints in the design process [2,3,4,5]. This paper seeks to incorporate systems-based economic and environmental objectives into retrofit process design using supply chain modeling and Life Cycle Assessment (LCA). These models are based on the outputs of an operations-driven cost model that integrates cost and process information for better

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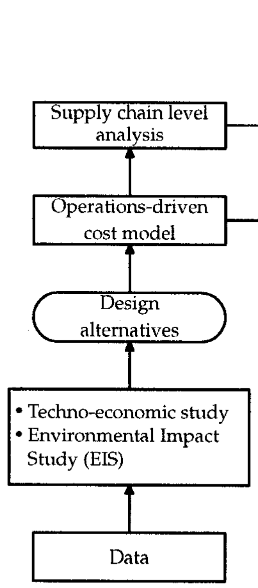

Fig. 1. Procedure for the implementation of the bottom-up business model approach for retrofit process design

characterization of manufacturing questions. A set of design alternatives is analyzed using all these models. The resulting information can then be used to choose the most preferred alternative using Multi-Criteria Decision Making (MCDM) (Fig. 1).

First, sustainability practices in chemical process design are reviewed and the objectives of this paper are given. Then, the retrofit design case study, the existing process and the design alternatives are described. Next, the supply chain model that was developed and the LCA methodology are described. Furthermore, several process scenarios are described that were used to obtain information about the behaviour of the alternatives under different market conditions. Then the results of the analyses for the case study are presented and discussed, followed by conclusions.

2. Sustainability in chemical process design

Process design decision making can become more sustainable by enlarging the system boundaries through the consideration of supply chain and life cycle aspects [6]. As a result, not only a process-based (or operations-driven) perspective is included in design, but also supply chain level aspects are considered. For instance, Beamon [7] mentioned that decisions on strategic facility location and material flow, which depends on the design of a process, are most substantially affecting the environment.

Shah [8] gave an overview of supply chain design, simulation and policy analysis and planning in the chemical industry. The goal of supply chain design is to increase shareholder value by making strategic decisions concerning this design, e.g. where to locate facilities or how to change existing facilities. For instance, retrofit process design including the supply chain using financial and cash management objectives has been carried out [9]. Shah [8] emphasized that much more benefit can be achieved by considering production aspects besides logistic ones, and the manufacturing complexity and efficiency of a plant. However, the author focused on supply chain considerations while taking into account process design. On the other hand, in order to practically include sustainable objectives into retrofit process design, the focus should be on the design first followed by the inclusion of supply chain level aspects.

The environmental dimension has mostly focused on the environmental performance of the process only and has not included supply chain considerations [10,11,12]. LCA [13] has been recognized as a powerful tool to model the environmental impact a product or process design may have along its life cycle [14,15]. It can be used beyond the boundaries of a production process and include the environmental impact of a complete supply chain [16]. Chevalier *et al.* [17] emphasized the close bond between LCA and chemical engineering, since it relies heavily on mass and energy balances and can create environmental performance indicators. LCA has been applied in process selection, design, and optimization for identifying clean technologies [14]. LCA provides, when applied correctly, knowledge regarding environmental trade-offs. Economic performance and LCA-based environmental objectives have been used in multi-objective optimization problems for process design and optimization [18,19]. This means that a balance needs to be found between the environmental burden and the traditional economic incentives. However, these applications did not include the supply chain perspective in their problem formulation. Most of the applications concerned greenfield design and almost none of them retrofit design. However, LCA challenges in greenfield design are very different from the ones in retrofit design. In greenfield design, everything is new and process data is not available [20]. However, in retrofit design, the challenge lies in the fact that a system with high intra- and inter-relations is modified which should be assessed carefully [21]. For this reason, there is a need for more work concerning integration of LCA in the retrofit process design.

Clift and Wright [22] discussed how environmental impacts and economic value build up along the supply chain of a product. Analysis of these build-ups is important for companies in order to position themselves in the supply chain according to their sustainable strategy and consequently to set their process design objectives. The Methodology for Environmental Impact Minimization (MEIM) incorporated the principles of LCA in a process optimization framework [23]. Hugo and Pistikopoulos [24] extended MEIM for establishing the trade-off between environmental damage and economic benefit at an industry-wide level along the supply chain and for providing an environmentally conscious basis for investment decisions. The methodology was applied to the process selection and the design of a greenfield supply chain such that the demand was satisfied over the whole planning horizon. This method contributes to the design of a greener supply chain and includes all elements of the traditional supply chain but may also include the collection, recycling, remanufacturing and re-use of products [25]. However, this method has only been applied for greenfield design projects and the focus is on the supply chain aspects while taking into account the process design. Azapagic *et al.* [26] proposed a methodology that integrates sustainability into process design and considered the product life cycle and complete design cycle, from project initiation to final design. In this methodology, all three sustainability dimensions were represented. However, this method also focused on greenfield process design and did not consider supply chain aspects.

The increased availability of process, cost and environmental data by the employment of information management systems at the plant level has resulted in opportunities for both process operations and design analysis. Janssen and Stuart [27] described a framework that is a bottom-up approach to using process, cost and environmental data in order to exploit their potential for process decision making based on process- and supply chain-level criteria. Retrofit process design may benefit substantially from this approach and lead to better design decisions since these data help to describe the interactions in the design that is modified. Furthermore, it considers the economic and environmental impact a design change may have at the supply chain level. This paper focuses on the supply chain level aspects of this framework applied to retrofit process design.

3. Objectives

The objectives of this paper are:
- To elaborate a methodology for analyzing enterprise-wide economic and environmental aspects based on an operations-driven cost model that characterizes alternatives for retrofit process design
- To provide supply chain and LCA results for retrofit design decision making specific to the case study.

4. Description of the retrofit design case study

4.1. *Energy considerations in an integrated newsprint mill*

This paper focuses on the supply chain level analysis of the implementation of increased de-inked pulp production and cogeneration at an integrated newsprint mill. The analysis fits within the business model framework that was introduced by Janssen and Stuart [27] (Fig. 1).
Newsprint production is an energy-intensive process because it requires large amounts of steam and electricity. This steam is produced in a boiler plant by burning fossil fuel and/or biomass. A big part of this steam is used in the paper machines for drying of the end product. Thermo-mechanical pulp (TMP) production requires large amounts of electricity due to its consumption by the TMP refiners. These refiners process wood chips to produce wood fibre and, as a by-product, low grade steam. On the other hand, DIP plant uses waste paper to produce fibre and uses much less electricity per tonne of fibre produced than a TMP plant. Partly or completely replacing TMP pulp production with increased production of de-inked pulp (DIP) will dramatically affect the mill-wide energy consumption. Also, due to an increase of steam production in the mill's boiler plant to compensate for the decrease of steam production in the TMP plant, the increase of DIP pulp production can give rise to a potential opportunity for cogeneration.
These potential changes also impact the supply chain of which the mill is a part. The supply of wood chips from nearby sawmills is replaced by the supply of waste paper from far away locations. This leads to increased costs and environmental impact due to transportation, but drastically lowers the electricity needs of the mill which has both a positive economic and environmental impact. Market conditions may affect the operation of the mill such that raw material requirements change (e.g. wood chips vs. waste paper) and may even lead to paper machine shutdowns and therefore lead to not meeting customer demand. Furthermore, increased use of biomass for generating steam in the boiler plant and the increased generation of electricity will have a positive environmental impact along the supply chain.

4.2. *Base case mill configuration*

The base case mill on which this study is based consists of the following production units (Fig. 2):
- 4 newsprint machines with a total average production of 1100 tonnes/day of newsprint
- 2 TMP lines with a total average production of 925 tonnes/day of pulp
- A DIP plant with a total average production of 175 tonnes/day of pulp, where 85% of the wastepaper used is old newspaper (ONP) and 15% is old magazine paper (OMG)
- A boiler plant that produces 7850 GJ/day of steam
- A back-pressure turbine that generates 0.4% of the total electricity demand of the mill.

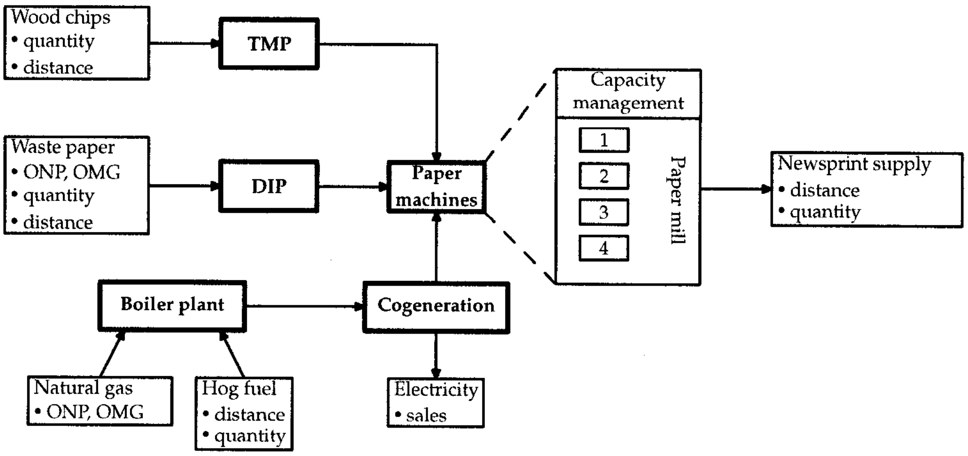

Fig. 2. Flow diagram of the integrated newsprint mill process main and inputs and outputs considered

Table 1
DIP plant configurations

Option	Configuration[a,b]
1	New 550 tonnes/day DIP plant, 1-loop
2	New 550 tonnes/day DIP plant, 2-loop
3	New 1100 tonnes/day DIP plant, 1-loop
4	New 1100 tonnes/day DIP plant, 2-loop
5	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop
6	Increase to 550 tonnes/day by adding a second line to the existing plant, 2-loop

[a] A 1-loop DIP system is a system that processes the waste paper in one alkaline cleaning stage. The 1-loop DIP technology is the more typical system used in North America

[b] A 2-loop system has an additional second cleaning loop that operates under acidic conditions. The 2-loop system provides more rigorous technology to compensate for the fact that the quality of waste paper is expected to degrade in the future [28]

Table 2
Cogeneration configurations

Option	Configuration
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines kept in service
B	New wood waste boiler (at very high pressure (VHP)) is installed. Half the boilers are upgraded to VHP operation. New backpressure turbine added to existing ones
C	New air-cooled condenser and condensing turbine are installed

4.3. *De-inking and cogeneration configurations*

The DIP plant process design configurations considered in the case study are an increase of DIP production to either 550 tonnes/day or 1100 tonnes/day (representing a 50% or 100% DIP integrated newsprint mill, respectively) (see Table 1). The cogeneration configurations have the following characteristics (see Table 2):

- Ability to increase biomass burning by the installation of hog fuel boilers,
- Reactivation of equipment that is currently idle (i.e., turbines to increase electrical output) and implementation of new back-pressure turbines or condensing turbines.

Table 3
Profitable design alternatives

Alternative	Description
1-A	New 550 tonnes/day DIP plant, 1-loop + cogeneration option A
1-B	New 550 tonnes/day DIP plant, 1-loop + cogeneration option B
3-A	New 1100 tonnes/day DIP plant, 1-loop + cogeneration option A
3-B	New 1100 tonnes/day DIP plant, 1-loop + cogeneration option B
3-C	New 1100 tonnes/day DIP plant, 1-loop + cogeneration option C
5-A	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop + cogeneration option A
5-B	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop + cogeneration option B

The following naming convention for the design alternatives was used: Alternative DIP configuration 1 to 6 as per Table 1-Cogeneration configuration A, B, or C as per Table 2. In total, 18 alternatives were analyzed in this case study by considering all possible combinations of the DIP and cogeneration configurations [5].
A detailed cost and profitability analysis was carried out for this design problem [29] and used an operations-driven cost approach that was described in [30]. This approach relates costs to processes in a given design alternative by identifying how raw materials are consumed by these processes and how these processes are related to the overall production cost. Mass and energy balances provided process data for each alternative. The profitability analysis revealed that seven out of eighteen alternatives were profitable (Table 3). These seven alternatives and the base case mill were then further analyzed using supply chain level analysis.

5. Methodology

5.1. *Overall approach*

The supply chain level analysis consisted of supply chain analysis and LCA. This analysis was carried out for the base case mill and each of the seven retained alternatives separately (Fig. 3). In this work, the social dimension has not been given enough justice and has therefore been omitted from the analysis.
The supply chain model is consistent with the mass and energy balances and the operations-driven cost model that was done (Fig. 3) [29]. Cost and production information generated by the cost model was used in the supply chain model. Unit resource costs were used to calculate the raw material (wood chips, waste paper, wood waste and natural gas), supplies, chemicals and electricity costs. The production information was used to characterize the manufacturing operations of the alternatives. Transportation costs were included in the raw material unit costs. The calculated overhead costs per tonne were transferred to the supply chain model and adjusted when necessary.
While classical LCA analysis, or attributional LCA (A-LCA), involves the assessment of environmental impacts of an entire product chain (i.e. from raw material extraction to final disposal of the product), C-LCA focuses on evaluating the changes in environmental impacts due to a modification in a given life cycle [31]. A-LCA fixes the system boundaries around the product chain. On the other hand, C-LCA involves an expansion of the boundaries to include all the processes that are affected by a decision whether or not they are part of the product chain and excludes the processes that are not affected. Another characteristic of C-LCA is the modeling of the affected marginal technology rather than the average technology. C-LCA was used in this study for two reasons. First, it generates more useful information for decision making [31]. Second, it allows for the comparison between an existing process design and the product chain it is part of and a retrofit of that design and possible changes in the product chain. The C-LCA directly used the

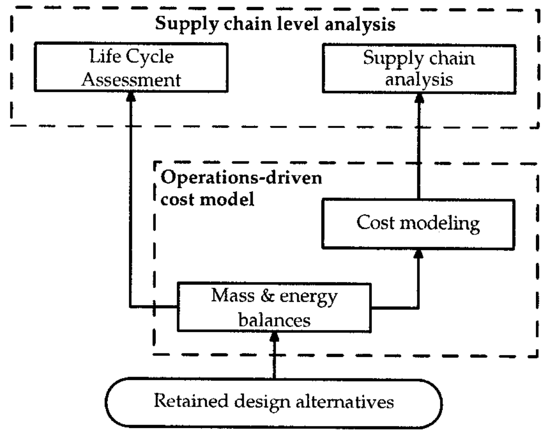

Fig. 3. Use of information by the supply chain level analysis

mass and energy balances that are part of the operations-driven cost model (Fig. 3). The material flows that were expected to show significant changes were selected and the information was extracted from this model. Next, the material flow data for the base case mill were subtracted from the corresponding data for all alternatives. The resulting difference values were then used as input for the C-LCA of the design alternatives.

5.2. *Supply chain model*

The purpose of the supply chain analysis was to investigate how market conditions may impact the operations for each design alternative and how this consequently may impact the supply chain. More specifically, the model focused on changes of the energy profile of the mill under different market conditions and how such changes may relate to the supply chain. For instance, at high electricity prices one or more paper machines may be shut down in order to minimize electricity use and to maximize electricity generation. This electricity could then be sold to the market at the high electricity price plus a premium. For this purpose, the operations and the supply of raw material and demand of product were modeled (Fig. 2). The resulting supply chain model considered the operation of the mill on a yearly basis. It is formulated as a Mixed-Integer Linear Programming (MILP) problem and maximizes the yearly profit of the design alternatives. It was implemented using the Solver in MS Excel [32]. The notation of the model variables and parameters is presented in Appendix A.

5.2.1. *Objective function*

The objective function calculates the supply chain profit per year of a design alternative based on the revenue of delivered newsprint and electricity generation minus a penalty cost for not meeting customer demand, minus the raw material cost, direct production department costs and overhead costs (eq. (1)).

$$
\begin{aligned}
\max \text{Profit} = & \underbrace{\sum_i \left(R_i D_i - R_i^{pen} \left(D_i^{max} - D_i \right) \right)}_{\text{revenue newsprint minus penalty}} + \underbrace{k C^E P^{TB}}_{\text{revenue cogeneration}} \\
& \underbrace{\underbrace{- \sum_q \left(\sum_{\substack{r \\ r \neq (steam,E)}} C_{r,q}^{PM} P_q^{PM} + \sum_{\substack{r \\ r = (steam,E)}} C_{r,q}^{PM} U_{r,q}^{PM} \right)}_{\text{paper machines (PMs)}} - \underbrace{\sum_p \sum_r C_{r,p}^{P} P_p}_{\text{all but PMs}}}_{\text{direct production department costs}} \\
& - \underbrace{\sum_s \sum_j C_{s,j}^S S_{s,j}}_{\text{raw material cost}} - \underbrace{C^{OH}}_{\text{overhead cost}}
\end{aligned}
\tag{1}
$$

The penalty cost accounts for the demand that is not met due to reduced production. Raw material cost included the cost of wood chips, waste paper, wood waste and natural gas. The direct production costs were calculated for each production department. The paper machine production costs were specified with more detail to account for the interaction of the individual paper machines with the other departments since each machine can operate at a slower production rate or be shut down completely (while obeying demand constraints). The steam and electricity costs per paper machine q were calculated using a linearized function for the steam and electricity consumption, $U_{r,q}^{PM}$ (r = {electricity, steam}). All other resource costs for the paper machines were calculated based on the production rate for paper machine q, P_q^{PM}. Likewise, the resource costs for the other production departments were calculated based on the production rate, P_p. For a given run of the model, the overhead cost was considered constant. However, it has been included in the objective function because it depends on model parameters, e.g. electricity price. These model parameters may be varied in the scenario analyses (see section 5.4).

5.2.2. *Manufacturing*

Newsprint production is bounded by a minimum and a maximum capacity of the paper machines. Also, the model allows shutting down each of the paper machines individually in order to obtain more flexibility in the trade-off between fibre and energy opportunities (eq. (2)).

$$
y_q P_q^{PM,min} \leq P_q^{PM} \leq y_q P_q^{PM,max} \qquad \forall q \tag{2}
$$

Since it is assumed that there are no yield losses in the paper machines, all of the produced pulp is used by the paper machines (eq. (3)). Furthermore, the pulp plants have a minimum and maximum capacity (eq. (4) and (5)).

$$
\sum_q P_q^{PM} = P^{TMP} + P^{DIP} \tag{3}
$$

$$
P^{TMP,min} \leq P^{TMP} \leq P^{TMP,max} \tag{4}
$$

$$
P^{DIP,min} \leq P^{DIP} \leq P^{DIP,max} \tag{5}
$$

The fraction of DIP pulp going to the paper machines in the 50% DIP design alternatives may vary between 0.25 ($Rmin^{DIP}$) and 0.75 ($Rmax^{DIP}$). The worst possible ratio, TMP:DIP = 25:75, is assumed to have the highest DIP pulp content that will not affect newsprint quality and paper machine operations for the given design alternatives without significant investment in the paper machines (eq. (6) and (7)).

$$RMin^{TMP}\sum_q P_q^{PM} \leq P^{TMP} \leq RMax^{TMP}\sum_q P_q^{PM} \tag{6}$$

$$RMin^{DIP}\sum_q P_q^{PM} \leq P^{DIP} \leq RMax^{DIP}\sum_q P_q^{PM} \tag{7}$$

The steam and electricity consumption of each paper machine shows non-linear behaviour and can be characterized by non-linear production functions [29]. In order to preserve linearity of the model, these functions have been linearized in the supply chain model by means of piecewise linearization.
The binary variable $t_{b,r,q}$ is used to select a segment of the piecewise linear function:

$$t_{b,r,q} = \begin{cases} 1 & \text{if b is the correct segment for paper machine } q \text{ and resource } r, \\ & r = \{\text{steam, electricity}\} \\ 0 & \text{if otherwise} \end{cases} \tag{8}$$

The bounds for steam and electricity consumption of each paper machine are defined by the upper and lower bounds for the paper machine capacities (eq. (2)). A set of constraints need to be obeyed for the piecewise linearization (eq. (9) to (14)). P_q^{PM} and $U_{r,q}^{PM}$ are written as a convex linear combination of the segment extremities, $\lambda_{a,r,q}$, on the segment that has been chosen by $t_{b,r,q}$ (eq. (9) and (10)).

$$P_q^{PM} = \sum_a \lambda_{a,r,q}\Psi_{a,r,q}^{PM} \qquad \forall q, r = \{\text{steam, electricity}\} \tag{9}$$

$$U_{r,q}^{PM} = \sum_a \lambda_{a,r,q}Y_{a,r,q}^{PM} \qquad \forall q, r = \{\text{steam, electricity}\} \tag{10}$$

The linear convexity of the combination is ensured (eq. (11)):

$$\sum_a \lambda_{a,r,q} = 1 \qquad \forall q, r = \{\text{steam, electricity}\} \tag{11}$$

Only one piecewise linear segment is chosen (eq. (12)):

$$\sum_b t_{b,r,q} = 1 \qquad \forall q, r = \{\text{steam, electricity}\} \tag{12}$$

For a selected segment, $t_{b,r,q}$, eq. (13) ensures that the appropriate values of $\lambda_{a,r,q}$ are selected.

$$\lambda_{a,r,q} \leq \sum_{\substack{b=a \\ a<NA}} t_{b,r,q} + \sum_{\substack{b=a-1 \\ a>1}} t_{b,r,q} \qquad \forall a, q, r = \{\text{steam, electricity}\} \tag{13}$$

$$0 \leq \lambda_{a,r,q} \leq 1 \qquad \forall a, q, r = \{\text{steam, electricity}\} \tag{14}$$

5.2.3. *Boiler plant*
The energy balance of an alternative is used to calculate the amount of electricity that is co-generated in the turbines as well as the energy input to the boiler plant. Capacity constraints for the boiler plant for each pressure level l were set (eq. (15)).

$$P_l^{BP,min} \leq P_l^{BP} \leq P_l^{BP,max} \qquad \forall l \tag{15}$$

The steam that is produced in the boiler plant and used in the process is lowered in pressure through turbines with the goal to maximize electricity production (eq. (16)). However, a part of the steam produced at high pressure, $M_{p,l}^D$ is also used at high pressure and not passing through a turbine (eq. (17)). This amount of steam was assumed to be 30% of the sum of the total steam use per paper machine (see eq. (10)). Also, steam is produced by the process, $M_{p,l}^S$ (eq. (18)), which may be used for electricity generation in the case of cogeneration option C using the condensing turbine.

$$\sum_t M_{t,l}^{TB} = \frac{P_l^{BP}}{H_l^{BP}} - \sum_p M_{p,l}^{D} + \sum_p M_{p,l}^{S} \qquad \forall l \tag{16}$$

$$M_{p,l}^{D} = \beta_{p,l}^{D} \sum_q U_q^{PM,steam} = \frac{h_{p,l}^{steam} P_p}{H_{p,l}^{steam}} \qquad \forall p,l \tag{17}$$

$$M_{p,l}^{S} = \frac{\phi_{p,l}^{steam} P_p}{H_{p,l}^{steam}} \qquad \forall p,l \tag{18}$$

Capacity constraints for the turbines were set:

$$\sum_l M_{t,l}^{TB} \leq M_t^{TB,max} \qquad \forall t \tag{19}$$

The total amount of generated electricity by the turbines is:

$$P^{TB} = \sum_t \sum_l \left(Y_t^{TB} \left(H_{t,l}^{TB,in} - H_{t,l}^{TB,out} \right) M_{t,l}^{TB} \right) \tag{20}$$

The fuels that are used in the boiler plant are wood waste, natural gas and sludge produced by the DIP and waste water treatment plants. The capacity of the boiler plant for using wood waste varies with the cogeneration configuration. Energy input to the boiler plant at the different pressure levels, E_l^{BP}, is a non-linear function of the steam production [29]. This behaviour is caused by the non-linearity of the boiler efficiency. In order to retain linearity of the formulation, energy input has been linearized instead of the boiler efficiency (eq. (21) to (27)).

$$t_{w,l} = \begin{cases} 1 & \text{if w is the correct segment for pressure level } l \\ 0 & \text{if otherwise} \end{cases} \tag{21}$$

$$P_l^{BP} = \sum_v \lambda_{v,l} \Upsilon_{v,l}^{BP} \qquad \forall l \tag{22}$$

$$E_l^{BP} = \sum_v \lambda_{v,l} \eta_{v,l}^{BP} \qquad \forall l \tag{23}$$

$$\sum_v \lambda_{v,l} = 1 \qquad \forall l \tag{24}$$

$$\sum_w t_{w,l} = 1 \qquad \forall l \tag{25}$$

$$\lambda_{v,l} \leq \sum_{\substack{w=v \\ v<NA}} t_{w,l} + \sum_{\substack{w=v-1 \\ v>1}} t_{w,l} \qquad \forall v,l \tag{26}$$

$$0 \leq \lambda_{v,l} \leq 1 \qquad \forall v,l \tag{27}$$

The energy input to the boiler plant at pressure levels l is the sum of fuel use plus the energy content of the returned condensate and fresh water (eq. (28) to (30)) (Fig. 4).

$$\begin{aligned} \sum_l E_l^{BP} =& H^{NG} \sum_s S_{s,j=NG} + H^{WW} \sum_j S_{s,j=WW} \\ &+ H^{DIP,sludge} r^{DIP,sludge} P^{DIP} + H^{WWT,sludge} P^{WWT,sludge} + E^{cond} + E^{FW} \end{aligned} \tag{28}$$

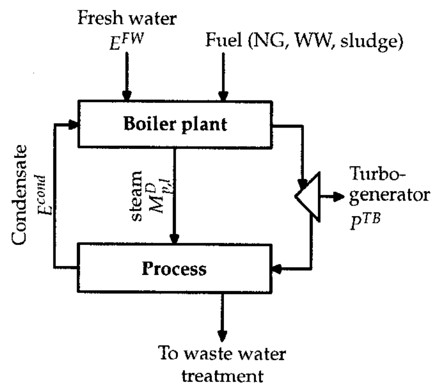

Fig. 4. Simplified representation of the interaction between the boiler plant and the production process

$$\begin{aligned} E^{cond} &= \underbrace{\alpha^{H,cond} f^{rec,cond} \left(\underbrace{\sum_l \frac{P_l^{BP}}{H_l^{BP}} + \sum_p \sum_l M^S_{p,l}}_{\text{total mill-wide steam production}} - \underbrace{\sum_p \sum_l \frac{f^{steam}_{p,l} P_p}{H^{steam}_{p,l}}}_{\text{total process steam use}} \right)}_{\text{condensate recovery in air-cooled condenser}} \\ &\quad + \underbrace{\alpha_p^H \sum_{\substack{p \\ p \neq PM}} f_p^{rec} P_p + \sum_q f_q^{rec,PM} U^{PM}_{r=steam,q}}_{\text{condensate recovery from process}} \\ &= \alpha^{H,cond} \mathbf{A} + \alpha_p^H \mathbf{B} + \mathbf{C} \end{aligned} \tag{29}$$

$$E^{FW} = \alpha^{H,FW} \left(\sum_l \frac{P_l^{BP}}{H_l^{BP}} - (\mathbf{A} - \mathbf{B}) \right) - \mathbf{C} \tag{30}$$

The energy content of the condensate, E^{cond}, consists of the energy content of the condensed steam that has been collected by the air-cooled condenser, $\alpha^{H,cond}\mathbf{A}$, and of the condensate that is recovered from the process, $\alpha_p^H \mathbf{B} + \mathbf{C}$. The α's are conversion factors to calculate the energy content of the condensate. The mass of steam recycled from the air-cooled condenser back to the boiler plant, **A**, consists of steam that is used only to cogenerate electricity and is not used by the process. It is calculated by subtraction of the total process steam use from the total mill-wide steam production. For instance, in the case of cogeneration option B, this is the excess amount of steam that is produced at very high pressure (VHP) and passes through a turbine to have its pressure reduced from VHP to atmospheric pressure.
The energy content of fresh water that is used, E^{FW}, is based on the difference of steam produced in the boiler plant and the amount of recovered condensate.

5.2.4. *Paper demand*

The customer base does not change with the alternatives. It was assumed that all produced newsprint is sold in the same year. Therefore, the production by the paper machines is equal to the delivered amount of newsprint. Inventory costs were not considered (eq. (31)).

$$\sum_q P_q^{PM} = \sum_i D_i \tag{31}$$

It is assumed that through contracts a minimum demand is guaranteed for each customer up to a maximum value D_i^{max}.

$$D_i^{min} \leq D_i \leq D_i^{max} \qquad \forall i \tag{32}$$

5.2.5. *Raw material supply*

The waste paper (ONP, OMG) and virgin fibre requirements by the pulp mills need to be satisfied:

$$P^{DIP} = \sum_s Y^{DIP} S_{s,j=\{ONP,OMG\}} \tag{33}$$

$$P^{TMP} = \sum_s Y^{TMP} S_{s,j=chips} \tag{34}$$

Finally, the use and supply of wood chips, old newsprint (ONP), old magazine (OMG) and wood waste varies with the alternatives. Their supply is limited and has a maximum.

$$S_{s,j} \leq S_{s,j}^{max} \qquad \forall s, j \tag{35}$$

5.3. *Consequential LCA modeling*

This study was performed using a methodological framework based on the ISO 14040 standard which consists of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation [33].

5.3.1. *Goal and scope definition*

The purpose of this study was to generate environmental information that will be used for decision making regarding the different design alternatives. The functional unit that was selected corresponded to the yearly newsprint production (387,200 admt). This functional unit was selected in order to be consistent with the supply chain analysis. Within the system boundaries, all activities that were affected by the implementation of the alternatives were contained, whether or not theses activities were within the boundaries of the newsprint life cycle. These activities mainly included the newsprint pulp and paper process itself and upstream activities to maintain it (chemical and fuel production, forest operations and fibre production as well as activities in other systems which are affected by changes in flows in the newsprint system (e.g. paper disposal, other consumers of recycled fibers, etc.). All assumptions regarding affected activities which were outside the newsprint life cycle are presented in Appendix B.

5.3.2. *Inventory*

In order to be practical, a study that involves the inclusion of only processes that are affected by the alternatives should be differential (i.e. difference with a status quo or base case). The foreground (mill processes) differential inventory data of each alternative was generated using the operations-driven cost model mentioned previously. All the generated flows were compiled in the SimaPro 7.0 LCA software. Since the operations-driven cost model was supplying only foreground inventory data, it was necessary to complete it with the most appropriate generic data for background inventory data (non-mill processes). For instance, if one alternative used a differential of +x kg of caustic (foreground data), the production of +x kg of caustic was modeled using generic data (background data). Most of the time, the generic data were taken from the

Table 4
Assumptions for the C-LCA of the retained design alternatives

Material flow	Assumption
Waste paper feedstock	All used waste paper is deviated from landfill
Chip consumption	Decrease in the consumption of wood chips in the design alternatives results in decreased wood chips production, which leads to a reduction of forest operations
Wood waste consumption	Forest residues are burned before replanting as a new source for wood waste

Table 5
Description of the scenarios

Parameters	Description
Electricity price	Electricity price was varied over a range of credible values, \$25–150 \$/MWh
Natural gas price[a]	Natural gas price was varied over a range of credible values, \$5–15 \$/MWh
Wood waste price and availability[a]	(i) Limited availability due to technical reasons (ii) Competition for wood waste. All additional wood waste (compared to the base case mill usage) has to be bought at a higher price
Waste paper price and availability[a]	Competitive market. All additional waste paper (compared to the base case mill usage) has to be bought at a higher price. Price increases of 10% and of 50% were considered at low, medium and high electricity price levels

[a] Electricity price: low = \$35/MWh, medium = 72 \$/MWh, high = 125 \$/MWh

ecoinvent 1.1 database. The retained design alternatives were subject to a set of assumptions in order to carry out the C-LCA as mentioned in Table 4.

5.3.3. *Impact assessment*

The impact assessment was carried out using the IMPACT 2002+ characterization method [34]. In this method, the inventory results are linked via fourteen midpoint categories to four damage categories (human health, ecosystem quality, resources and climate change). The utilization of the damage categories as decision criteria is very practical from a decision making standpoint compared to a midpoint method, because it involves a smaller number of indicators that are more meaningful for decision makers. However, endpoint methods generate more modeling uncertainties than midpoint methods [35]. For this case study, sensitivity analyses showed that the utilization of either of these sets of criteria (midpoint or damage categories) would lead to a similar decision most of the time. In order to increase the comprehensibility of the results for decision makers, normalization of impact assessment results is often performed. In order to do so, it is necessary to define a meaningful reference. In this case, the initial life cycle environmental performance of the investigated newsprint was selected (using a cradle-to-gate approach, i.e. from forest operation to distribution). Next, the results were expressed as a percentage of this initial performance. A result of plus or minus X% indicated that the change in environmental impact caused by an alternative was equivalent to X% of the initial life cycle environmental impact of the newsprint, the positive case indicating deterioration and the negative case improvement.

5.3.4. *Interpretation*

In this step, the results were assessed in order to make conclusions and recommendations.

5.4. *Scenario development*

A set of supply chain scenarios was defined to investigate the impact of different market conditions on the performance of the retained design alternatives (Table 5). Tables B.1 to B.3 (see Appendix B) give the assumptions for each of these market scenarios. The model parameters

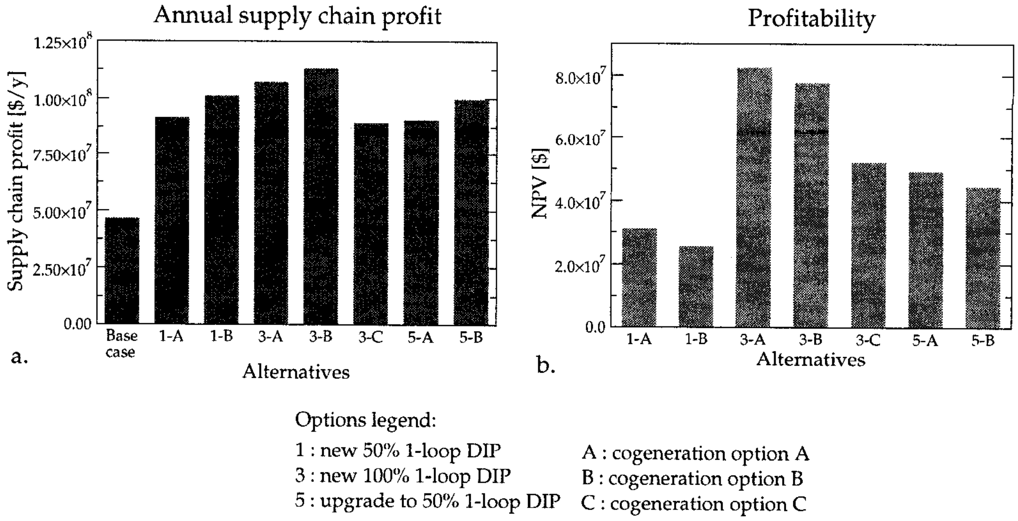

Fig. 5. Annual supply chain profit and profitability for the retained design alternatives and the base case mill

that were varied were the electricity and natural gas prices, wood waste price and availability and waste paper price and availability. Varying electricity and natural gas prices may lead to market conditions that will impact the production strategy and may therefore lead to changing product chain performance. Variation in wood waste and waste paper prices and availability may have a similar effect.

6. Results and discussion

6.1. *Supply chain analysis of the retained design alternatives*

The supply chain profit for all retained design alternatives is higher than for the base case mill (Fig. 5a). The difference in supply chain profit between them is mostly due to the difference in the amount of electricity cogenerated. Furthermore, it should be noted that the design alternative with the highest profitability does not have the highest supply chain profit (Fig. 5b) [29]: alternative 3-B has the highest annual supply chain profit, whereas alternative 3-A is most profitable (when compared to the base case mill). Alternative 3-B achieves a higher profit than alternative 3-A due to the higher income it gains from selling cogenerated electricity, but has a lower profitability because it requires a higher investment.

6.2. *C-LCA of the retained design alternatives*

The environmental impact of the retained design alternatives improves significantly when compared to the base case mill (Fig. 6a). All impact categories show a decreased environmental impact compared to the base case mill with the 100% DIP alternatives showing the biggest improvement. This is due to reduced TMP pulp production (50% DIP alternatives) or shutdown of the TMP plant (100% DIP alternatives). Consequently, the use of the marginal technology for electricity generation is reduced (coal incineration) which reduces the environmental impact sig-

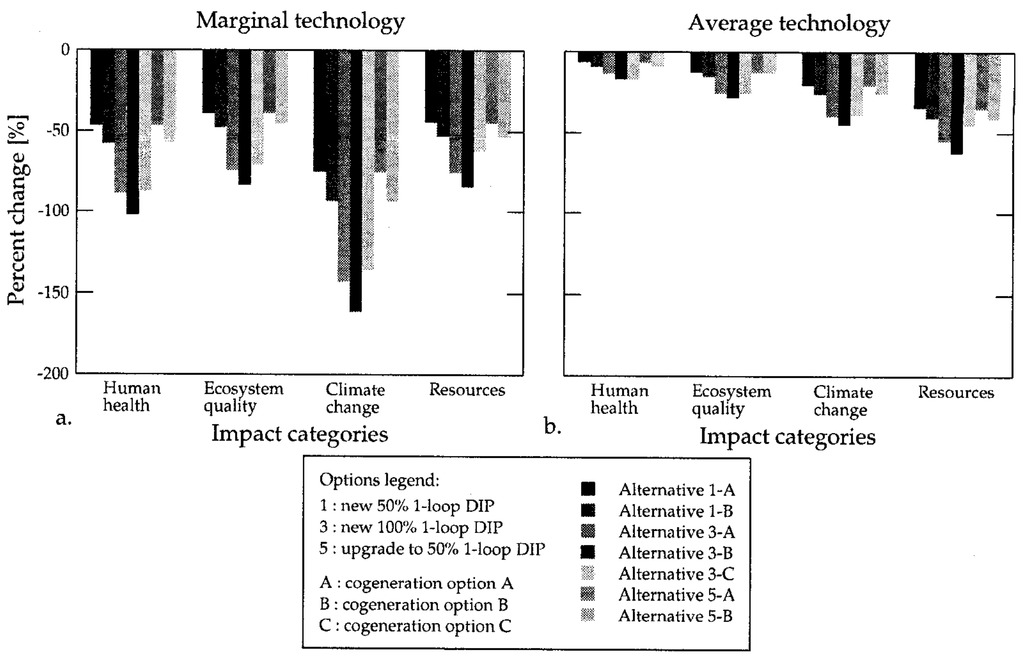

Fig. 6. Result of the LCA for the retained design alternatives considering a change in using: a. marginal technology (coal incineration) for electricity generation only, b. average technology for electricity generation (grid fuel mix: 33% burning coal, 39% nuclear energy, 28% hydropower)

nificantly.

The most profitable alternative, alternative 3-A, is outperformed by alternative 3-B for all the environmental impact categories. Alternative 3-B outperforms all other alternatives for each indicator, because the TMP plant is shut down and cogeneration option B has the biggest electricity generation capability. Consequently, this alternative uses a minimum amount of electricity and best avoids the production of electricity by the marginal technology.

Although procedures for choosing the marginal technology exist [36], it remains a task that can lead to different results depending if short- or long-term horizons are taken into account and if the market is decreasing, stable or growing. For this reason, the effect of this choice was tested. When considering decreased use of the average technology for electricity generation, the improvement of environmental performance is smaller compared to reduced use of the marginal technology (Fig. 6b). This is due to the fact that a decrease in electricity production then affects the total grid fuel mix. All changes that result in decreased use of the marginal technology are worthwhile from an environmental standpoint. In this case study, the grid fuel mix was 33% coal, 39% nuclear energy and 28% hydropower.

6.3. *Analysis of design scenario results*

6.3.1. *Energy related scenarios*

The electricity price was varied for the base case mill and the retained design alternatives to determine its impact on the annual supply chain profit (Fig. 7). For the range of electricity prices considered, the base case mill design is the least favorable design. The annual profit declines

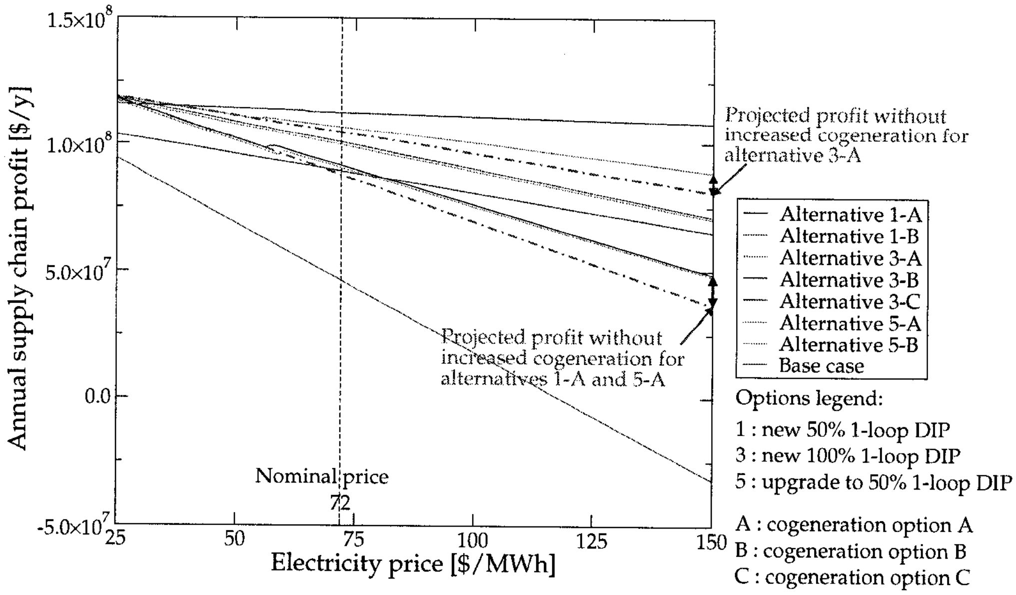

Fig. 7. Annual supply chain profit for the base case mill and design alternatives with varying electricity price

much faster for the base case mill because of higher electricity use in the TMP plant when compared to the retained design alternatives. At an electricity price of 118 $/MWh, this even leads to a negative annual profit.

The supply chain profit for the 50% DIP design alternatives (alternatives 1-A, 1-B, 5-A and 5-B) declines more rapidly with increasing electricity price than for the 100% DIP design alternatives (alternatives 3-A,B and C). This is due to higher electricity consumption because of more TMP pulp production in the 50% DIP alternatives. Consequently, alternative 3-C becomes more profitable than alternatives 5-A and 5-B at an electricity price of $80/MWh. It should be noted that there was no change in total newsprint production for the electricity price range considered. Newsprint production always generates a profit for the range of electricity prices and is therefore maximized.

The annual supply chain profit is affected by the natural gas price for the base case mill and alternative 3-C only, due to their default use of natural gas for steam production. On the other hand, the natural gas price slightly impacts the supply chain profit of the other alternatives although they use no natural gas. This is because the natural gas price is used for calculation of the of cost of mixed and DIP sludge use for steam production.

After inspection of the optimization results, a step change in wood waste use was found at a certain electricity price, most notably for the design alternatives with cogeneration option A (Fig. 8). At electricity prices below this so-called cross-over price, less steam is produced in the boilers and therefore there is less electricity generation. At these prices, the design alternative is more profitable when producing only the steam needed by the process, whereas above the cross-over price it becomes profitable to produce excess steam for more electricity generation. The increased use of wood waste above the cross-over price does not lead to a significant increase in the profit for alternatives 1-A and 5-A (Fig. 7). The revenue due to higher electricity generation is mostly offset by the higher electricity cost for running the process and the cost of

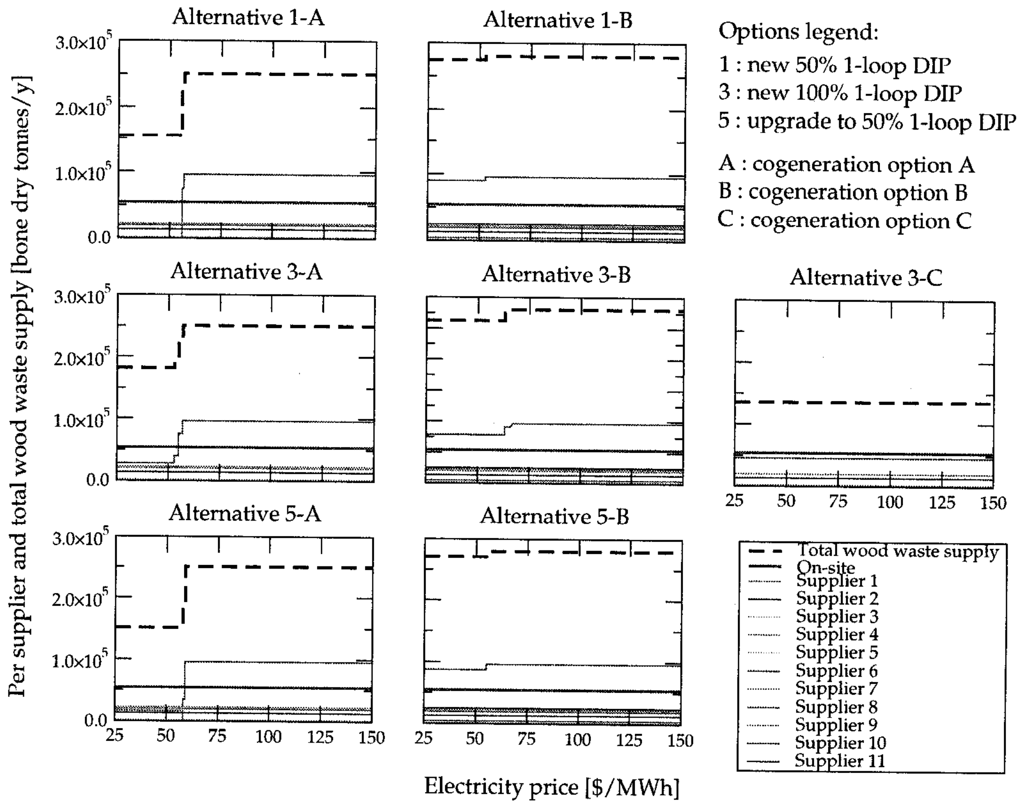

Fig. 8. Wood waste supply changes for the design alternatives with varying electricity price

extra wood waste used. However, it should be noted that the profit for these alternatives declines at a slower rate at higher electricity prices due to more cogeneration. The environmental impact did not change much because of varying wood waste use (Fig. 9 and Table B.1). For instance, the climate change impact for alternative 3-A improved step-wise from -135% below the cross-over price to only -142% above the cross-over price. This 7% climate change impact improvement results in an annual profit decrease of only 0.3% around the cross-over price. However, the annual supply chain profit continued to decrease while the environmental improvement stayed the same above the cross-over price.
Larger wood waste capacity and production of very high pressure (VHP) steam in the alternatives with cogeneration option B results in lower steam production costs and increased cogeneration potential. Consequently, the change in wood waste use is small for these alternatives in order to maximize the annual profit. Only alternative 3-C does not show a change in wood waste use. The wood waste capacity of this alternative cannot is not big enough to satisfy the mill steam demand and therefore the maximum amount of wood waste plus an additional amount of natural gas is burned.

Wood waste availability had a significant effect on the supply chain profit of the alternatives (Fig. 10). For this analysis, it was assumed that there is no competition for wood waste and that its price remains at the base case value for all alternatives. However, at this price less wood

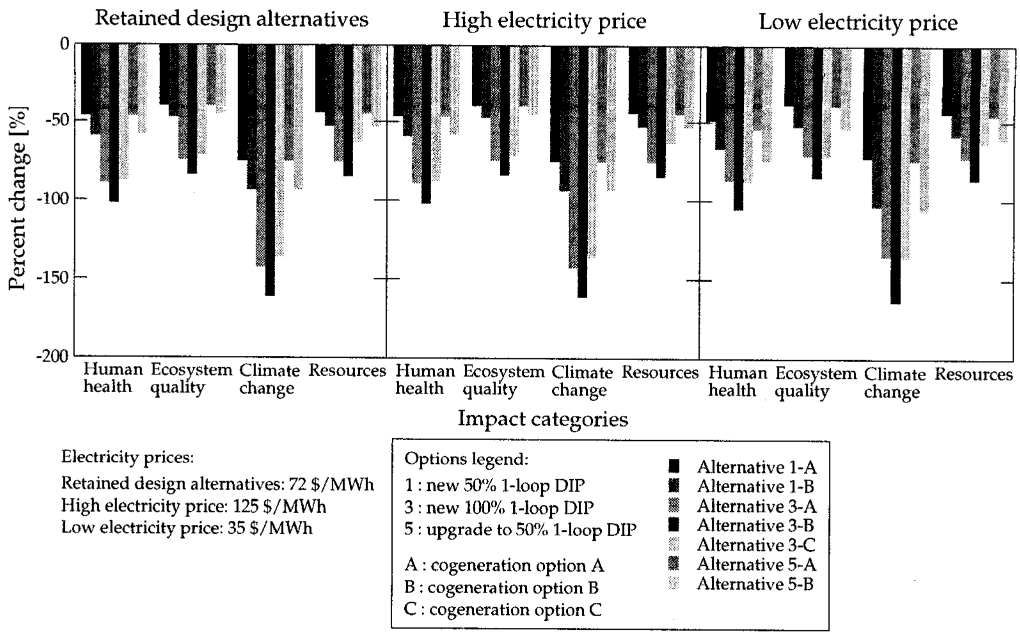

Fig. 9. Result of the LCA for the retained design alternatives for high and low electricity price scenarios

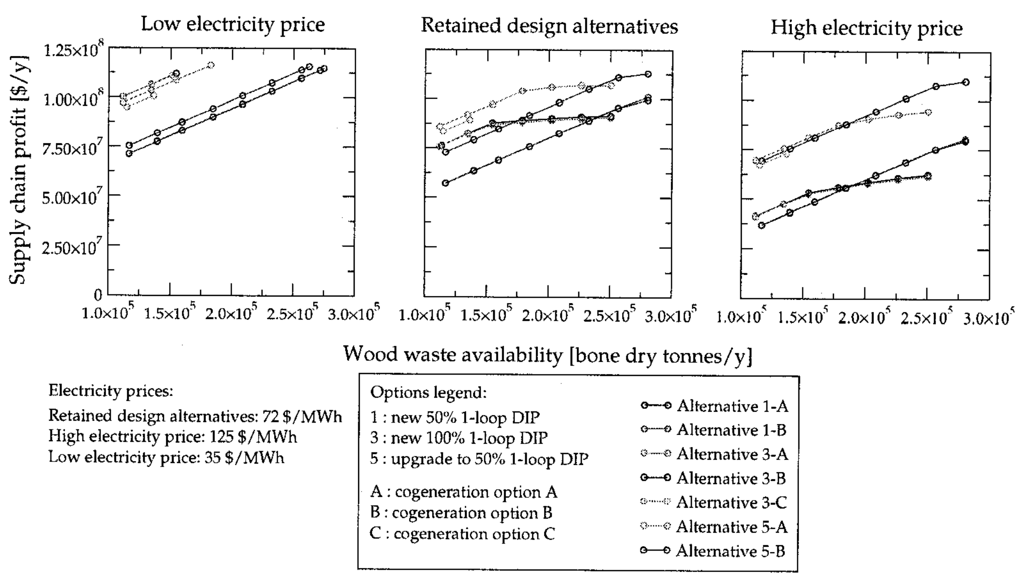

Fig. 10. Annual supply chain profit for the design alternatives with varying wood waste availability at low, base case and high electricity prices, and no competition for wood waste

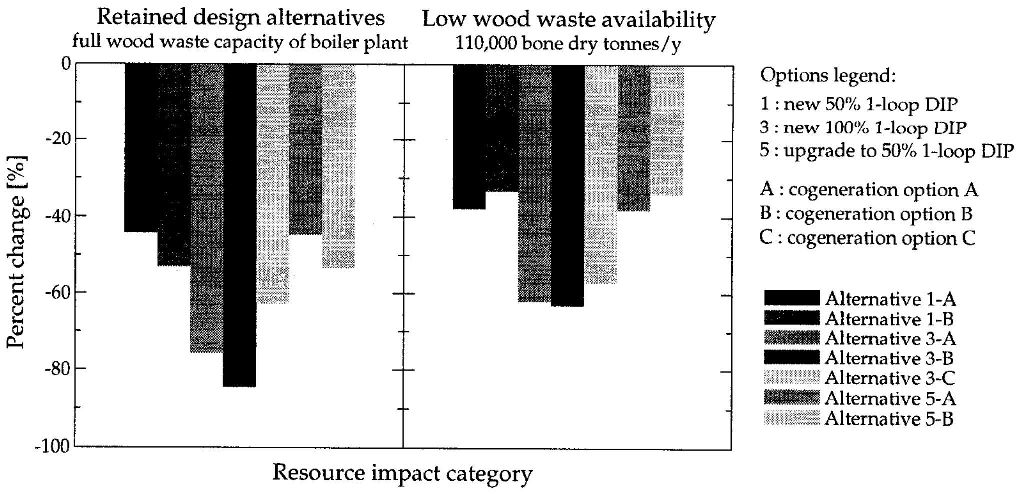

Fig. 11. Resource impact for the design alternatives considering low wood waste availability under non-competitive market conditions: 110,000 bone dry tonnes/year available at base case price

waste may be available due to technical reasons. Furthermore, it was assumed that the mill has control over the supplier mix. For the retained design alternatives with cogeneration option A, a decrease in wood waste availability had a minor effect on supply chain profit at first. This effect was attenuated when natural gas started to be used as a replacement fuel due to its higher price. For alternatives 1-A and 5-A this occurred at $1.5 \cdot 10^5$ bone dry tonnes/y of wood waste and for alternative 3-A at $1.8 \cdot 10^5$ bone dry tonnes/y. Natural gas will be used if wood waste is not the only fuel that can satisfy process steam demand. Consequently, there will be no excess steam production and electricity generation will not change because the natural gas cost for producing excess steam outweighs any profit that can be made with the generated electricity. At low electricity prices (35 $/MWh), the optimal wood waste use by alternatives 1-A, 3-A and 5-A is lower (see Fig. 8). Nevertheless, under these circumstances they are the most profitable alternatives.
The alternatives with cogeneration option B start to use natural gas almost as soon as wood waste availability decreases because electricity generation is maintained at a high level. In this case, the profit from generating electricity outweighs the cost of steam production, even though this means a faster decline of the annual profit. As a result, alternatives 1-B, 3-B and 5-B have a lower profit than the other alternatives at low wood waste availability except for alternative 3-B at high electricity price.
At low wood waste availability (for all electricity prices), the design alternatives show an increase in the resources indicator for all alternatives and thus a lower environmental performance while the other indicators practically stay the same (Fig. 11 and Table B.2). This is due to increased natural gas use. Therefore, from a resource use standpoint, lower wood waste availability is both economically (Fig. 10) and environmentally undesirable.
In another analysis, it was assumed that there is competition for wood waste and that all additional wood waste used compared to the base case mill needs to be purchased at a higher price. Competition for wood waste means that all extra wood waste use will be deviated from another system. Since wood waste is used for electricity generation, this wood waste is replaced by the marginal technology in that other system. For all alternatives, the annual supply chain profit decreased slightly at a higher wood waste price, because the higher cost of wood waste is still low compared to the cost of the other raw materials and natural gas. On the other hand, considering

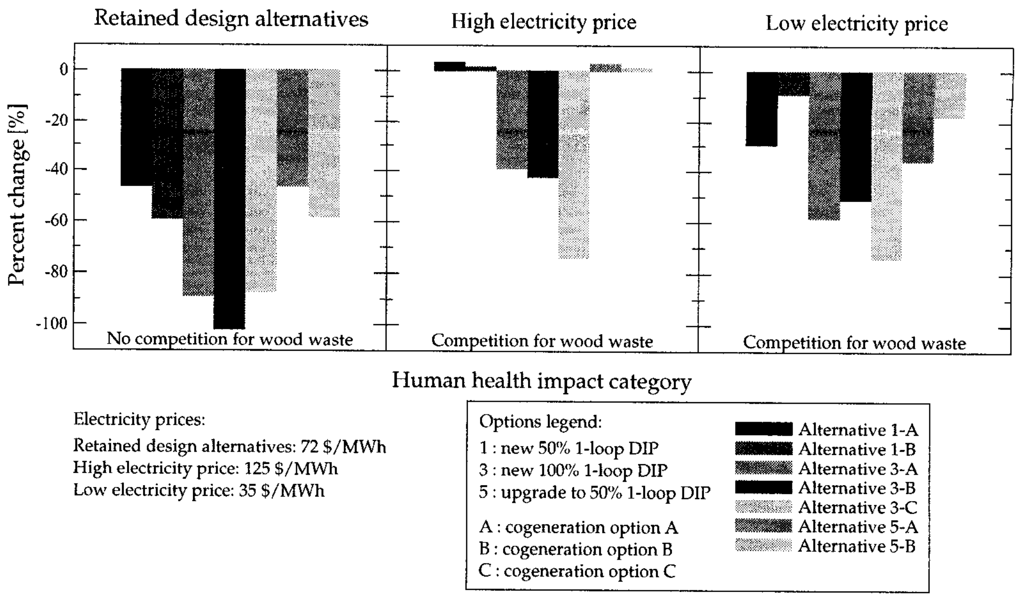

Fig. 12. Human health impact for the design alternatives for wood waste availability under competitive market conditions: All additional wood waste (compared to the base case mill usage) is bought at a higher price

competition for wood waste had a more significant impact on the environmental performance of the alternatives, especially for the human health category at high and low electricity prices (Fig. 12 and Table B.2). At high electricity price, this scenario even showed a deterioration of the human health indicator for the 50% DIP alternatives compared to the base case mill.

6.3.2. *Competitive waste paper market*

It was assumed that there is competition for waste paper due to a higher industry-wide demand. Consequently, a higher price needed to be paid for the additional waste paper that was used compared to the base case mill. The waste paper price was increased by 10% and 50% and its impact was calculated for varying electricity prices (Fig. 13). A 10% increase of waste paper price did not show a large impact on profit when compared to the base waste paper price. A 50% increase in waste paper price shows more profound changes. The 100% DIP alternatives suffer the largest negative impact of an increased waste paper price on their profit, especially at low electricity price. At that price, all of the 50% alternatives are more profitable than the 100% alternatives. At higher electricity prices the 100% alternatives become more profitable again because the 50% DIP alternatives are more affected by higher electricity price.

Competition for waste paper results in deviation of all extra waste paper use from other systems instead of from landfill. These systems consequently need to use more virgin pulp by increasing TMP and Kraft pulp production. The C-LCA results for these scenarios show that if waste paper is diverted from other systems, the increase in environmental performance is smaller compared to the retained design alternatives, especially for the 100% DIP design alternatives (Fig. 14 and Table B.3). Only climate change impact hardly changes because energy consumption remains almost constant in this comparison. It should be noted that at low electricity price (35 $/MWh) and high waste paper price (50% increase) the ratio of TMP and DIP pulp going to the paper machines changes for the 50% DIP alternatives. For this scenario, the ratio of TMP to DIP is equal to

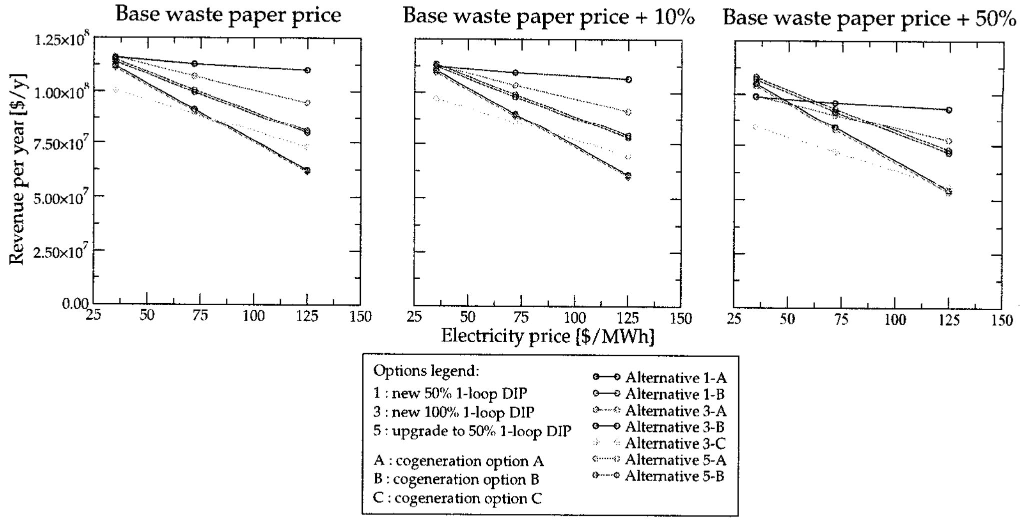

Fig. 13. Annual supply chain profit for the design alternatives under competitive market conditions for waste paper with a 10% and 50% waste paper price increase

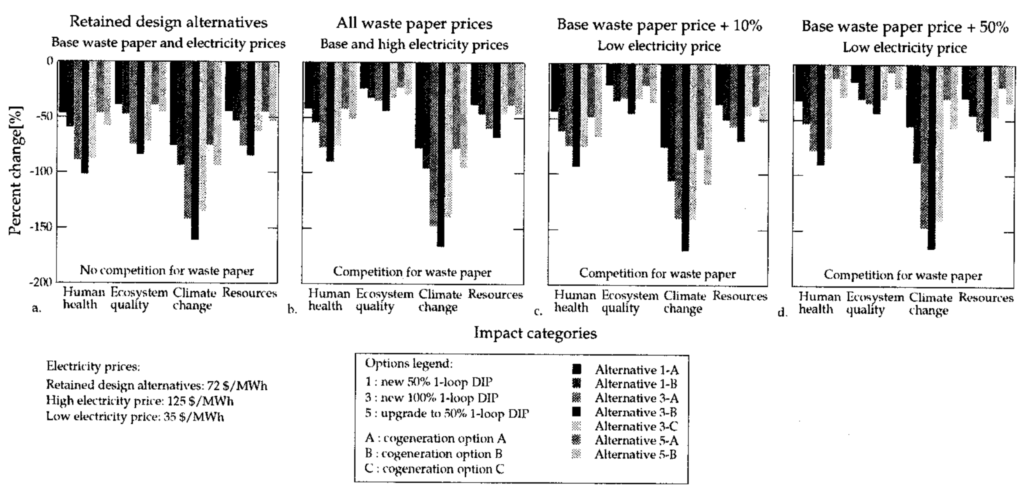

Fig. 14. Result of the LCA for the design alternatives for waste paper availability under competitive market conditions: 10% and 50% waste paper price increase

56% TMP to 44% DIP, whereas for all other instances the TMP to DIP ratio is equal to 44% TMP to 56% DIP. This results in a lower overall environmental improvement of the 50% DIP design alternatives when compared to a 10% increase of the waste paper price (Figs. 14c and 14d).

7. Conclusions

This paper presented the supply chain level aspects of a new methodology for retrofit process design. The supply chain level analysis was carried out using supply chain and LCA models.

Process and cost data were used in an operations-driven cost model in order to provide the supply chain and LCA models with consistent information that accurately reflected changes in process design and operations thus linking process to the supply chain in a bottom-up manner. Therefore, the supply chain level analysis yielded information about the performance of the retrofit design alternatives under various scenarios based on process-level data. Regulations force the design alternatives to be environmentally compliant at the process level and act as constraints on the feasibility of them. The use of LCA besides supply chain analysis allowed the identification of trade-offs between environmental and economic objectives at the supply chain level and could therefore lead to more sustainable retrofit design decision making because of an expansion of the system under study.

Scenario analysis shows trends that are useful for decision making, but when taking into account multiple criteria, it is important to carry out a systematic analysis in order to determine their relative importance. The case study demonstrated that the inclusion of product chain analysis may lead to different decisions when compared to decisions based on traditional economic analysis. The most profitable retrofit design is not necessarily the alternative with the best performance from a supply chain perspective (Fig. 5). However, this would depend on the importance that the decision makers would give to profitability and the annual supply chain profit, respectively.

Acknowledgements

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A. Model notation

Table A.1: Model notation for the supply chain model

Sets and indices	
$i \in \mathcal{I}$	customers, $i = 1,\dots,$NC
$s \in \mathcal{S}$	suppliers, $s = 1,\dots,$NS
$r \in \mathcal{R}$	resources (steam, electricity, chemicals and supplies) $r = 1,\dots,$NR
$j \in \mathcal{J}$	raw materials, $j = 1,\dots,$RM
$p \in \mathcal{P}$	production departments $p = 1,\dots,$NP
$q \in \mathcal{Q}$	paper machines $q = 1,\dots,$NQ
$t \in \mathcal{T}$	turbines $t = 1,\dots,$NT
$l \in \mathcal{L}$	pressure level in boiler plant, $l = 1,\dots,$NPL
$a \in \mathcal{A}$	segment extremities of non-linear function for steam use in paper machines $a = 1,\dots,$NA
$b \in \mathcal{B}$	segments of piecewise linearized function for steam use in paper machines $b = 1,\dots,$NA-1
$v \in \mathcal{V}$	segment extremities of non-linear function for fuel use in boiler plant $a = 1,\dots,$NV
$w \in \mathcal{W}$	segments of piecewise linearized function for fuel use in boiler plant $a = 1,\dots,$NV-1
Continuous variables	
Profit	Supply chain profit per year for the design alternative [$/y]
Following variables ≥ 0	
P_p	Production by department p in [unit produced/y]
P_q^{PM}	Production by paper machine q [tonnes/y]
P^{TMP}	Production by the TMP plant [tonnes/y]
P^{DIP}	Production by the DIP plant [tonnes/y]

Continued on next page

Table A.1 – continued from previous page

P_l^{BP}	Steam production in the boiler plant at steam pressure level l[GJ/y]
P^{TB}	Total electricity generated in the turbines [MWh/y]
D_i	Delivered newsprint to customer i [tonnes/y]
$S_{s,j}$	Supply of raw material j by supplier s [tonnes/y]
$U_{r,q}^{PM}$	Resource use r of paper machine q (defined for r = {electricity, steam}, otherwise 0) [units used/y]
E_l^{BP}	Energy input to the boiler plant to produce stam at steam pressure level l[GJ/y]
E^{cond}	Total heat of returned condensate [GJ/y]
E^{FW}	Total heat of fresh water [GJ/y]
$M_{t,l}^{TB}$	Mass flow of steam at pressure level l going to turbine t [tonnes/y]
$M_{p,l}^{D}$	Steam use by production department p at pressure level l (not used for cogeneration [tonnes/y]
$M_{p,l}^{S}$	Steam supply by production depratment p at pressure level l (not used for cogeneration [tonnes/y]
$\lambda_{a,r,q}$	Defines point on segment of piecewise linearized function for paper machine q and resource r (r = {steam, electricity })
$\lambda_{v,l}$	Defines point on segment of piecewise linearized function for boiler plant fuel use at steam pressure level l
Binary variables	
y_q	Takes the value of 1 when a paper machine is running, otherwise 0
$t_{b,r,q}$	Takes the value of 1 if b is the correct segment of the piecewise linearized function for paper machine q and resource r (r = {steam, electricity }), otherwise 0
$t_{w,l}$	Takes the value of 1 if w is the correct segment of the piecewise linearized function for boiler energy input at steam pressure level l, otherwise 0
Model parameters	
k	Premium on the electricity price for selling generated electricity [-]
C^E	Electricity price [$/MWh]
$C_{s,j}^S$	Cost of raw material s from supplier j [$/tonne]
$C_{r,q}^{PM}$	Cost per unit of resource r for paper machine q [unit of resource/tonne]
$C_{p,r}^{P}$	Cost per unit of resource r for production department p
C^{OH}	Overhead costs of the mill [$/y]
R_i	Revenue of newsprint sales per customer i [$/tonne]
R_i^{pen}	Penalty cost from customer i for not meeting demand [$/tonne]
D_i^{min}	Minimum delivered newsprint to customer i [tonne/y]
D_i^{max}	Maximum delivered newsprint to customer i [tonne/y]
$S_{s,j}^{max}$	Maximum supply of raw material j by supplier s [tonne/y]
$P^{TMP,min}$	Minimum production of TMP pulp [tonne/y]
$P^{TMP,max}$	Maximum production of TMP pulp [tonne/y]
$P^{DIP,min}$	Minimum production of DIP pulp [tonne/y]
$P^{DIP,max}$	Maximum production of DIP pulp [tonne/y]
$P_q^{PM,min}$	Minimum capacity of paper machine q [tonne/y]
$P_q^{PM,max}$	Maximum capacity of paper machine q [tonne/y]
$P^{WWT,sludge}$	Sludge production in the waste water treatment plant [tonne/y]
$P_l^{BP,min}$	Minimum capacity of the boiler plant at steam pressure level l [GJ/y]
$P_l^{BP,max}$	Maximum capacity of the boiler plant at steam pressure level l [GJ/y]
$M_t^{TB,max}$	Maximum capacity of turbine t [tonnes/y]
$RMin^{TMP}$	Mimimum fraction of TMP pulp used by the paper machines
$RMax^{TMP}$	Maximum fraction of TMP pulp used by the paper machines
$RMin^{DIP}$	Minimum fraction of DIP pulp used by the paper machines
$RMax^{DIP}$	Maximum fraction of DIP pulp used by the paper machines
$f^{rec,cond}$	Fraction of condensate from air-cooled condenser returning to the boiler plant [-]
$f_{p,l}^{steam}$	Factor for calculating steam use at pressure level l by production department p based on production by this department [GJ/unit produced]
f_p^{rec}	Fraction of condensate from process (all but paper machines) returning to the boiler plant [-]
$f_q^{rec,PM}$	Fraction of condensate from paper machines returning to the boiler plant [-]

Continued on next page

Table A.1 – continued from previous page

$h^{steam}_{p,l}$	Factor for calculating steam demand at pressure level l by production department p based on production by this department (steam not passing through a turbine) [GJ/unit produced]
$r^{DIP,sludge}$	Ratio of DIP sludge production and DIP pulp production [tonne DIP sludge/tonne DIP]
$H^{steam}_{p,l}$	Heat content of the steam used by production department p at pressure level l [GJ/tonne]
H^{NG}	Heat content of natural gas [GJ/m^3]
H^{WW}	Heat content of hog fuel [GJ/tonne]
$H^{DIP,sludge}$	Heat content of DIP sludge [GJ/tonne]
$H^{WWT,sludge}$	Heat content of waste water treatment sludge [GJ/tonne]
H^{BP}_{l}	Heat content of the steam produced at steam pressure level l [GJ/tonne]
$H^{TB,in}_{t,l}$	Heat content of the steam input to turbine t at pressure level l [GJ/tonne]
$H^{TB,out}_{t,l}$	Heat content of the steam output from turbine t at pressure level l [GJ/tonne]
γ^{TMP}	Yield of the TMP plant [-]
γ^{DIP}	Yield of the DIP plant [-]
Y^{TB}_{t}	Efficiency of turbine t [MWh/GJ]
α^{H}_{p}	Factor for converting mass flow of condensate from process to heat flow for production department p (all but paper machines) [GJ/tonne]
$\alpha^{H,cond}$	Factor for converting mass flow of condensate from air-cooled condenser to heat flow [GJ/tonne]
$\beta^{D}_{p,l}$	Fraction of total steam use for paper machine p that is used at pressure l
$\alpha^{H,FW}$	Factor for converting mass flow of fresh water to heat flow [GJ/tonne]
$\phi^{steam}_{p,l}$	Factor for calculating steam production at pressure level l by production department p based on production by this department [GJ/unit produced]
$\eta^{BP}_{v,l}$	Segment extremity a of piecewise linear function of the boiler plant energy input at steam pressure level l [GJ/y]
$\Psi^{BP}_{v,l}$	Segment extremity a of piecewise linear function of the boiler plant at steam pressure level l [GJ/y]
$\Psi^{PM}_{a,q}$	Segment extremity a of piecewise linear function of paper machine q [tonne/y]
$\Upsilon^{PM}_{a,r,q}$	Segment extremity a of piecewise linear function for resource use r of paper machine q steam use (r = {steam, electricity}) [units used/y]

B. Descriptions of the scenarios and their assumptions

Table B.1. Base design, electricity price and natural gas price scenarios

SCENARIOS		ASSUMPTIONS REGARDING THE AFFECTED FLOWS				
Description	#	Chips	Waste paper	Electricity	Natural gas	Wood waste
Base design alternatives scenario	0	Chips are available at the base case price. *(Chip reduction results in reduced chip production and reduced forest operations).*	Waste paper is available at the base case price. *(Waste paper availability increases with the demand meaning that more paper is deviated from landfill).*	Electricity is available at the base case price (medium). *(A decrease of electricity consumption or an increase of electricity production at the mill will result in a decrease of electricity production by the marginal technology at the power grid (coal)).*	Natural gas is available at the base case price. *(Natural gas is considered as unconstrained. A change in the investigated system results in a proportional change in production).*	Wood waste is available at the base case price. *(Wood waste is considered unconstrained meaning that there is unused waste available. It has been assumed that extra waste required is currently incinerated without energy recovery).*
Electricity price variation						
High price	1a	Same as scenario 0	Same as scenario 0	Electricity price is higher than the base design.	Same as scenario 0	Same as scenario 0
Low price	1b			Electricity price is lower than the base design.		
Natural gas price variation						
Varying natural gas price at high electricity price	2a			Electricity price is higher than the base design.		
Varying natural gas price at medium electricity price	2b	Same as scenario 0	Same as scenario 0	Base design electricity price.	Variable natural gas price	Same as scenario 0
Varying natural gas price at low electricity price	2c			Electricity price is lower than the base design.		

Table B.2. Wood waste availability scenarios

SCENARIOS		ASSUMPTIONS REGARDING THE AFFECTED FLOWS				
Description	#	Chips	Waste paper	Electricity	Natural gas	Wood waste
Due to technical reasons, only a limited amount of wood waste is available. High electricity price.	3a	Same as scenario 0	Same as scenario 0	Electricity price is higher than the base design.	Has to increase in order to compensate for lack of wood waste availability.	Only 20,000 tonnes/year extra (compared to base case) are available at base case price. [a]
Due to technical reasons, only a limited amount of wood waste is available. Medium electricity price.	3b			Base design electricity price.		
Due to technical reasons, only a limited amount of wood waste is available. Low electricity price.	3c			Electricity price is lower than the base design.		
Competition for wood waste. High electricity price.	3d	Same as scenario 0	Same as scenario 0	Electricity price is higher than the base design.	Same as scenario 0	All additional wood waste (compared to base case) has to be bought at higher price. [b]
Competition for wood waste. Medium electricity price.	3e			Base design electricity price.		
Competition for wood waste. Low electricity price.	3f			Electricity price is lower than the base design.		

[a] Wood waste is considered unconstrained only to the base case price level

[b] There is competition for wood waste which means that all extra wood waste use in this system will be deviated from another system and replaced by the marginal technology in this other system (coal burning).

Table B.3. Waste paper availability scenarios

SCENARIOS		ASSUMPTIONS REGARDING THE AFFECTED FLOWS				
Description	#	Chips	Waste paper[a]	Electricity	Natural gas	Wood waste
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (10%). High electricity price.	4a			Electricity price is higher than the base design.		
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (10%). Medium electricity price.	4b			Base design electricity price.		
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (10%). Low electricity price.	4c	Same as scenario 0	Waste paper becomes more expensive with additional use of the process when compared to the base case.	Electricity price is lower than the base design.	Same as scenario 0	Same as scenario 0
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (50%). High electricity price.	4d			Electricity price is higher than the base design.		
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (50%). Medium electricity price.	4e			Base design electricity price.		
There is competition for waste paper. Additional waste paper (compared to the base case) is available at a higher price (50%). Low electricity price.	4f			Electricity price is lower than the base design.		

[a] Competition for waste paper means that waste paper is deviated from other systems. It has been assumed that it is deviated from paper production in other systems has to be compensated by the use of TMP and kraft pulp. If there is no competition for waste paper, it is assumed that the waste paper is deviated from landfill.

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A.4 Multi-criteria decision making for retrofit process design using process- and supply chain-level criteria

Multi-criteria decision making for retrofit process design using process- and supply chain-level criteria

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Abstract

The chemical engineering community has mostly focused on the generation of optimal process design alternatives using optimization techniques. When considering multiple objectives, a set of optimal alternatives is found, yet the most preferred alternative remains to be determined. This paper addresses a decision making method using Multi-Attribute Utility Theory (MAUT) for determining the most preferred retrofit design alternative based on economic and environmental objectives. An expert decision panel was carried out in order to determine the most preferred alternative. The panel members had engineering, corporate and environmental backgrounds. Process- and supply chain-level metrics were used as the attributes in order to calculate the utility of the decision criteria and a trade-off method was used to determine the importance of the criteria. This resulted in the determination of the preferred retrofit design alternative. Subsequently, Monte Carlo analysis refined the results of the decision analysis. This method enables a more balanced design decision making and can lead to different decisions compared to traditional approaches using profitability as sole objective.

Key words: Retrofit process design, Design decision making, Multi-criteria decision making, Process-level criteria, Supply chain-level criteria

1. Introduction

The many technological advances and efficiency improvements of industrial processes in the recent past have not been able to compensate the unprecedented rate of change in the consumption of goods due to the emergence of large new economies. More dramatic changes in how these goods are produced and consumed are necessary to obtain a more sustainable growth.

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This requires initiatives that have as a goal to not only consider the traditional economic growth indicators during the decision making stages, but also consider the environmental and societal consequences of the actions that are taken.
In engineering, decisions made on a corporate or facility level have historically been money-driven. Process design studies were carried out using methodologies that considered economic objectives and used environmental regulations only as constraints for the examined design alternatives (Fisher et al. (1987); Nelson and Douglas (1990); Ng (2004); Smejkal et al. (2005); Uerdingen et al. (2005)). However, with the growing environmental consciousness of society, the impact of a process or product upon the environment is playing an increasingly larger role in the decision making process (Suslick and Furtado (2001)). This transforms the traditional single criterion decision making problem (based only on economic considerations) into a far more complex one. A thorough analysis must be carried out to make well-informed and more sustainable decisions. Multi-Criteria Decision Making (MCDM) methods are tools for systematically analyzing such complex problems by reflecting the preferences of the decision makers.

2. Multi-Criteria Decision Making methods

2.1. *Decision analysis*

Decision analysis, defined as "a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney (1982)), can be carried out with Multi-Criteria Decision Analysis (MCDA). MCDA methods can be classified into two groups: multi-attribute decision analysis and multi-objective optimization (Seppälä (2003)). Multi-objective optimization is a technique that has been widely used for the optimization of existing processes and the design and synthesis of new processes taking into account both environmental and economic objectives (Alexander et al. (2000); Diwekar (2003)). Although multi-objective optimization generates optimal alternatives, it does not determine the most appropriate alternative based on the preference of the decision maker.
Decision analysis consists of four steps (Fig. 1) (Keeney (1982)). First, the decision problem is structured by specifying the objectives, criteria and their attributes, and alternatives. Second, the possible impact of alternatives is assessed. When feasible, models should be developed to determine probabilities of consequences of the alternatives. The consequences of an alternative determine the criteria for the decision and these are characterized or quantified by attributes. The criteria, and consequently the attributes, need to reflect the objectives of the decision, i.e. if the decision is based on economic and environmental objectives, then the consequences of choosing an alternative need to be measured with economic and environmental attributes. Third, the preference of the decision makers is elicited by determining decision weights and utility functions for each of the criteria. Utility is a measure for the attractiveness based on a decision maker's preferences. Consequently, an utility function is a rule by which this assignment is carried out and depends on the preferences of a single decision maker. The utility function reflects the preference over a range of attribute values. Finally, the alternatives are compared and evaluated, and a sensitivity analysis is carried out.

2.2. *Multi-Attribute Utility Theory*

One theory for describing the preference of a decision maker using multiple objectives (and consequently multiple criteria) is Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa (1976)). MAUT is based on expected utility theory, which attempts to describe and quantify

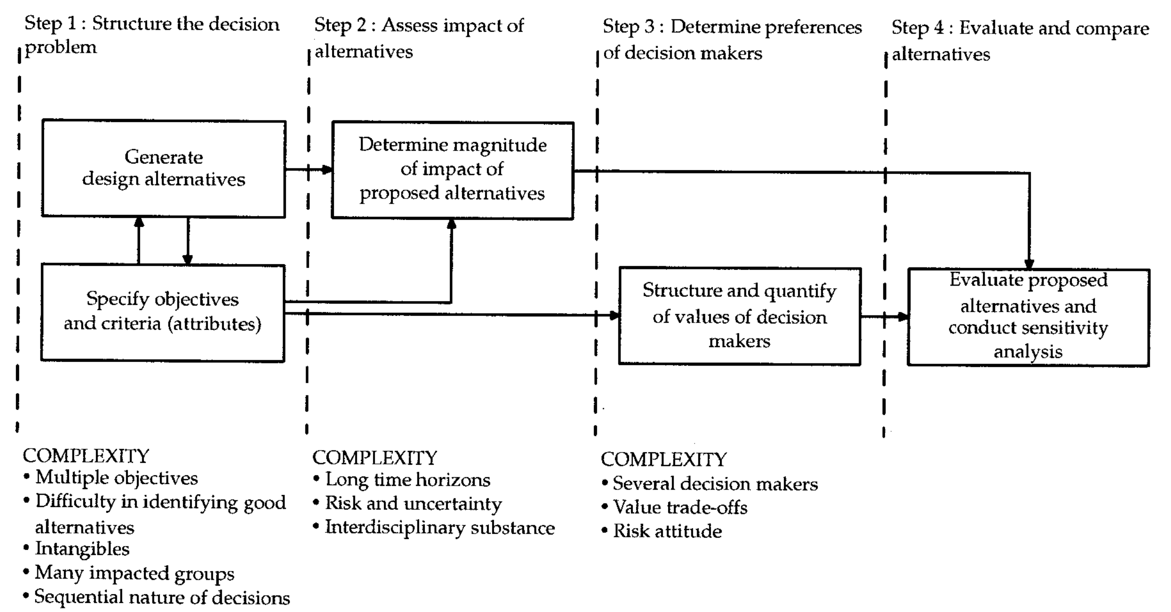

Fig. 1. Schematic representation of the steps of decision analysis (based on Keeney (1982))

preferences for decision making under uncertainty. Utility theory can be used when the decision maker does not exactly know the consequences of a decision that will be made. Von Neumann and Morgenstern (1953) defined a set of axioms such that expected utilities or expected utility functions are a good measure for consistent and rational decision making. Over the years, several works have pointed out violations of the axioms on which utility theory and thus MAUT are based (see e.g. Kahneman & Tversky (1979)). However, MAUT can still be used for decision-making by making the appropriate assumptions.
Using MAUT, two characteristics need to be determined for an attribute:

- The preference the decision maker has over a range of attribute levels
  This is done by determining the utility function over a range of values for an attribute (criteria are quantified by attributes). This can therefore be characterized as an *intra*-comparison of preference for attribute levels.
- The importance of an attribute compared to the other ones.
  This is done by determining the decision weight of an attribute. This is characterized as an *inter*-comparison of importance between attributes.

In order to define a multi-attribute utility function, some independence conditions need to be satisfied. First, utility independence implies that the value of the utility function for one attribute does not depend on another. For instance, if in the two-dimensional utility function $u(y, z^0)$, y is utility independent of z^0, it can be simplified to $u(y)$. Therefore, utility independence helps to simplify and structure the problem (Keeney and Raiffa (1976)). Secondly, additive independence permits the summation of each individual utility function to give the overall utility function:

$$u(x) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{1}$$

with:
$u(x)$ = overall utility function
k_i = decision weight with $\sum_{i=1}^{N} k_i = 1$ and $0 \leq k_i \leq 1$
u_i = utility function of attribute i
N = number of defined criteria
$u_i(x_i)$ = utility function for attribute i

Process design decision making based on multiple objectives, for which discrete design alternatives are known beforehand, has not been dealt with extensively. MAUT has been applied for the selection of technology for solid residuals treatment at a mill (Duarte (2001)). Five alternatives were identified and the criteria were economic cost, image (regarding market and public), environmental impact, flexibility (regarding regulations and plant evolution), and runnability. Dimensionless attributes were used to characterize environmental impact and technical issues. These attributes used discrete dimensionless scales to describe preference. Cost aspects were based on both capital and operating expenditures, and were measured in monetary values.
A MAUT model was proposed for improving investment decisions in petroleum exploration by taking into account technological advancement, capital, and environment (Suslick and Furtado (2001)). MAUT was also combined with uncertainty propagation models to capture the trade-off between an economic and an environmental attribute in one value. This would prevent the designer having to spend considerable amounts of time examining graphs that depict this trade-off (Cano-Ruiz (1999)).

2.3. *Decision-Based Engineering Design*

Decision-Based Engineering Design (DBED) is a methodology that was developed in the mechanical engineering community and is based on the notions of utility theory (Hazelrigg (1998)). DBED seeks to base engineering design decisions on information obtained from various sources, not necessarily all related to the engineering disciplines. DBED is a good demonstration of the applicability of MAUT in engineering design, but its application to chemical engineering design has not been found in the literature. There are similarities between chemical process synthesis and DBED, but the methodology cannot be used for a process design decision in which the discrete alternatives are already known beforehand. Rather, the optimal design is determined by optimization of the overall utility function (Thurston (1990); Thurston and Srinivasan (2003)), and therefore leads to the generation of one optimal alternative. Nevertheless, the overall utility function that is constructed may contain both economic and environmental attributes.

2.4. *Analytic Hierarchy Process*

The Analytic Hierarchy Process (AHP) is a decision methodology based on the pair-wise comparison between attributes (Saaty (1980, 1990b)) and has also been applied in chemical engineering problems to consider economic and environmental objectives (Eagan and Weinberg (1999); Zhou et al. (2000); Wen and Shonnard (2003)). The method uses importance ratio judgments between each pair of attributes at a given hierarchical level. These levels need to be defined by the decision maker. Using the outcome of these pair-wise comparisons, the preferences of the decision-maker are determined. There has been a debate between the proponents of AHP and utility theory concerning the validity of both methods (Dyer (1990); Harker and Vargas (1990); Saaty (1990a)). AHP has been criticized especially for its axiomatic foundations and the phenomenon of rank reversal and may therefore not reflect the true preferences of the decision maker (Dyer (1990)). Recently, it was shown that rank reversal is a mathematical consequence of the normalization procedure of the AHP (Moffett et al. (2006)). On the other hand, AHP proponents criticize the assumptions made in utility theory and the use of lotteries to elicit preferences (Saaty (1990a)).

2.5. *Decision weighting*

The aggregation of individual utility functions into an overall function is done by weighting these functions obeying eq. (1). These weights represent the importance of each attribute. The overall utility function reflects the preference of the decision maker based on all the attributes. Distance-to-target methods have attempted to relate a valuation weighting factor to a defined impact category target by comparing actual environmental performance with a goal or standard. However, it was shown that these methods cannot be used as a weighting method (Finnveden (1999)). The targets serve as a reference point for the decision maker and not as a weighting scheme.

Cornejo et al. (2005) developed a methodology to improve Environmental Impact Assessment (EIA) for industrial projects by including LCA considerations. This was done by execution of an MCDM expert panel. The panel members were asked to weight the EIA and LCA criteria that were selected. These criteria were presented to the panel members as normalized values based on the base case values (i.e. values for an existing integrated newsprint mill). Also, the target value for each of the criteria was given as a reference. AHP was used as the weighting

method. The result was an overall single-number metric, called the Environmental Index (EI). This methodology demonstrated the use of the distance-to-target concept as a reference for environmental decision making. Since all alternatives met environmental regulations, more weight was given to the LCA metrics than to the EIA metrics.
For guaranteeing a consistent decision making methodology, target values should also be employed for economic criteria. For instance, the target that a company sets for the profitability of a design project may be that the Internal Rate of Return (IRR) needs to be greater than 20%. Using these targets, design alternatives can be valuated by comparing their IRRs to the set targets. This gives the decision makers a more direct and transparent view on the differences between design alternatives. At the same time, these targets should be used as bounds for the ranges over which the utility functions are valid and trade-offs between the different criteria should be made (Keeney (2002)).

3. Description of the retrofit design case study

3.1. *Energy considerations in an integrated newsprint mill*

Newsprint production is an energy-intensive process because it requires large amounts of steam and electricity. This steam is produced in a boiler plant by burning fossil fuel and/or biomass. A big part of this steam is used in the paper machines for drying of the end product. Thermo-mechanical pulp (TMP) production requires large amounts of electricity to transform wood chips into wood fibre and produces low grade steam as a by-product. A number of techniques have been available to reduce the electricity consumption but they yield only marginal gains in electricity use. On the other hand, a de-inked pulp (DIP) plant uses waste paper to produce fibre and uses much less electricity per tonne of fibre produced than a TMP plant. In this context, partly or completely replacing TMP pulp production with increased production of de-inked pulp will dramatically affect the mill-wide energy consumption. Also, due to an increase of steam production in the mill's boiler plant to compensate for the decrease or absence of steam production in the TMP plant, the increase of DIP pulp production can give rise to a potential opportunity for cogeneration.
Increased production of DIP pulp production and implementation of cogeneration will have economic and environmental consequences. In order to make a well-informed and more sustainable design decision, these consequences need to be captured by the appropriate selection of a set of economic and environmental criteria and attributes.

3.2. *Base case mill configuration*

The base case mill on which this study is based consists of the following production units:
- 4 newsprint machines with a total average production of 1100 tonnes/day of newsprint,
- 2 TMP lines with a total average production of 925 tonnes/day of pulp,
- A DIP plant with a total average production of 175 tonnes/day of pulp, where 85% of the wastepaper used is old newspaper (ONP) and 15% is old magazine paper (OMG).

Furthermore, the following supporting processes are part of the base case mill configuration:
- A wastewater treatment plant that processes 50,000 m^3/day,
- A boiler plant that produces 7850 GJ/day of steam,
- A back-pressure turbine that generates 0.4% of the total electricity demand of the mill.

Table 1
DIP plant configurations

Option	Configuration
1	New 550 tonnes/day DIP plant, 1-loop
2	New 550 tonnes/day DIP plant, 2-loop
3	New 1100 tonnes/day DIP plant, 1-loop
4	New 1100 tonnes/day DIP plant, 2-loop
5	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop
6	Increase to 550 tonnes/day by adding a second line to the existing plant, 2-loop

Table 2
Cogeneration configurations

Option	Configuration
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines are kept in service
B	New wood waste boiler (at very high pressure (VHP)) is installed. Half the boilers are upgraded to VHP operation. New backpressure turbine is added to existing ones
C	New air-cooled condenser and condensing turbine are installed

3.3. *De-inking and cogeneration configurations*

The DIP plant process design configurations considered in the case study are an increase of DIP production to either 550 tonnes/day or 1100 tonnes/day (representing a 50% or 100% DIP integrated newsprint mill, respectively) (see Table 1). During the definition stage of the design alternatives, it was decided to consider both the 1-loop and 2-loop DIP technologies. A 1-loop DIP system is a system that processes the waste paper in one alkaline cleaning stage, whereas a 2-loop system has an additional second cleaning loop that operates under acidic conditions making it a more rigorous cleaning process. The 1-loop DIP technology is the more typical system used in North America, and its capital cost is lower when compared to a 2-loop system with the same capacity. On the other hand, the 2-loop system provides more rigorous technology to compensate for the fact that the quality of waste paper is expected to degrade in the future (Cody (2003)). The cogeneration configurations have the following characteristics (see Table 2):
- Ability to increase biomass burning by the installation of hog fuel boilers,
- Reactivation of equipment that is currently idle (i.e., turbines to increase electrical output) and implementation of new back-pressure turbines or condensing turbines.

In total, 18 alternatives were analyzed in this case study by considering all possible combinations of the DIP and cogeneration configurations (Janssen et al. (2006)). The design alternatives were named as clarified by the following two examples: Alternative 1-A represents the alternative with a 50% 1-loop DIP configuration (Table 1) and a cogeneration configuration that has one natural gas boiler converted to burn wood waste and the existing backpressure turbines are kept in service (Table 2). Likewise, alternative 3-C represents the alternative with a 100% 1-loop DIP configuration and a cogeneration configuration with a new air-cooled condenser and a new condensing turbine.

4. Methodology

4.1. *Operations-driven retrofit design approach*

This paper focuses on a MCDM panel that was carried out to decide about what design alternative should be implemented according to the preferences of the panel members. This is the last step in the bottom-up business model approach (Fig. 2) whose framework was first introduced

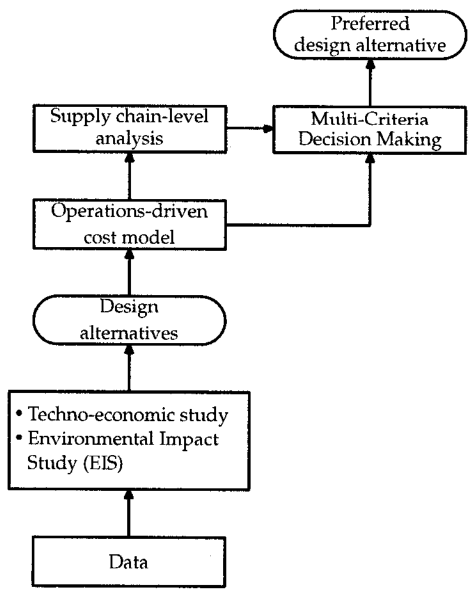

Fig. 2. Case study procedure for the implementation of the operations-driven retrofit design approach

by Janssen and Stuart (2004). This framework uses a bottom-up approach to using process, cost and environmental data in order to exploit their potential for process decision making based on multiple criteria.

First, a conventional techno-economic study was done in order to generate the retrofit design alternatives (Janssen et al. (2006)). Next, a detailed cost and profitability analysis was carried out for this design problem (Janssen et al. (2007b)). This analysis used an operations-driven cost modeling approach that was described by Laflamme-Mayer *et al.* (2007). This approach relates costs to processes in a given design alternative by identifying how raw materials are consumed by these processes in the alternative and how these processes are related to the overall production cost of the alternative. It directly used process data coming from the mass and energy balances of each alternative. The profitability analysis revealed that seven out of eighteen alternatives were profitable. These seven alternatives and the base case mill were then further analyzed using a supply chain model and LCA model to investigate the impact on the supply chain level of the retrofit changes at the process level (Janssen et al. (2007a)). Each of these modeling steps generates metrics that can be used as attributes for economic and environmental criteria (see 4.2.1).

4.2. *MCDM methodology*

An expert decision panel was formed to reflect the decision making process in "the real world". The members of this panel each brought their expertise to evaluate the design alternatives. This meeting of different fields of expertise allowed for the evaluation of the alternatives from an economic, environmental and process engineering perspective. Furthermore, the goal was to raise the panelists' awareness about the complexity of the decision problem when confronted with the views and preferences of the other panelists. MAUT was chosen as the decision analysis framework, because it provides a more robust method for the elicitation of the

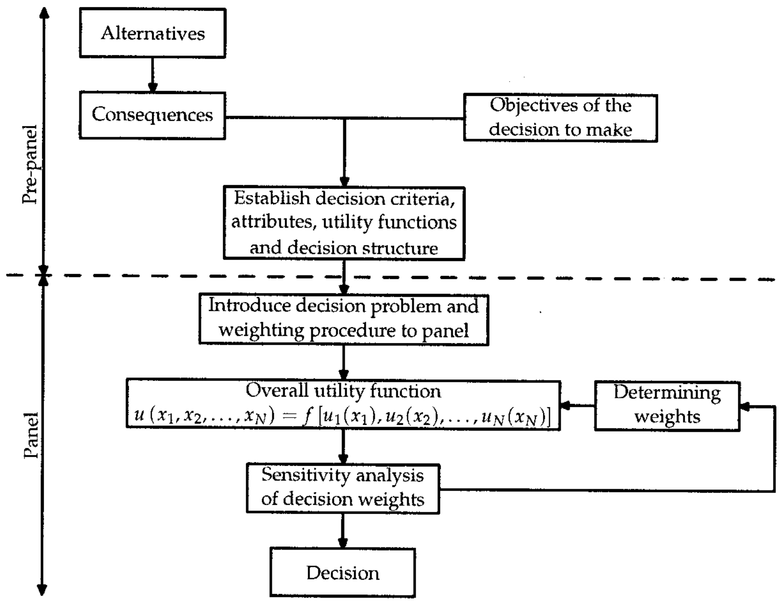

Fig. 3. Determination of the multi-attribute utility function

Table 3
Economic decision criteria

Criterion	Attribute	Justification for use
Investment	Total capital cost [$]	The pulp and paper industry has limited access to capital
Profitability	Internal Rate of Return [%]	Its target value is usually set by a company
Energy economics	Electrical self-sufficiency [%]	Reflects the mill's independence on external energy sources
Supply chain profit	Annual profit [$/y]	Market conditions may have an impact on the operations, the supply of raw materials or the demand of newsprint

preferences of the panel members. The following stages were carried out (Fig. 3):

(i) The objectives, the decision criteria and their attributes, utility functions and decision structure were defined before the assembly of the decision panel
(ii) The panel was introduced to the background of the decision problem and the procedure for eliciting the decision weights clarified and discussed
(iii) The overall utility function was obtained by determining the weights assigned to each individual utility function
(iv) Sensitivity analysis was carried out to determine how the importance of the attributes may affect the final decision.

The panel consisted of two members that have corporate positions in the pulp and paper industry, one engineering consultant, one LCA expert and one expert in sustainable development. One full day was used for running the decision panel.

4.2.1. *Decision objective, criteria & attributes*

The objective of the decision panel is to choose the preferred retrofit design alternative based on the importance and preference assessment by the panel members for the relevant environmental and economic criteria. In total, four economic and four environmental criteria were selected (Tables 3 and 4). The economic criteria were selected based on their relevance to the de-

Table 4
Description of the damage categories used in the IMPACT 2002+ method (Jolliet et al. (2003))

Category	Unit	Description
Human health	DALY	DALY stands for Disability Adjusted Life Years. Characterizes the severity of the impact of a substance, accounting for both mortality (Years of Life Lost (YLL) due to premature death) and morbidity
Ecosystem quality	PDF.m^2.yr	The impact on ecosystem quality is quantified by Potentially Disappeared Fraction of species per m^2 and per year
Climate change	kg_{eq} CO_2	The impact on climate change is measured with equivalent kilograms of carbon dioxide. This impact can be interpreted as damage on life support systems that deserve protection for their own sake
Resources	MJ	The impact on resource use is measured in megajoule. This amount of energy is the additional primary energy required per unit of mineral and of total non-renewable primary energy for energy carriers

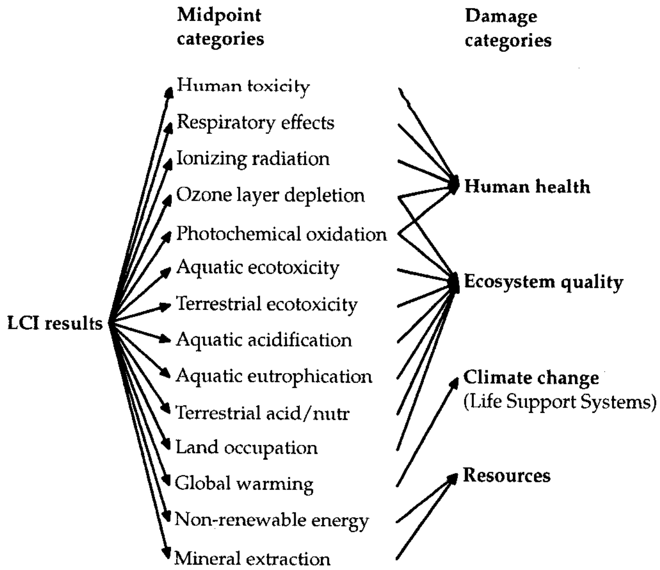

Fig. 4. Overall representation of the IMPACT 2002+ framework which connects 14 midpoints categories to 4 damage (endpoint) categories

cision problem. The environmental criteria were the damage categories as they are defined in the IMPACT2002+ method (Jolliet et al. (2003)). This life cycle impact assessment methodology quantifies the environmental impact of the design alternatives by linking life cycle inventory results to the four damage categories using 14 midpoint categories (Fig. 4). The utilization of the damage categories as decision criteria is practical from a decision making standpoint compared to a midpoint method because it involves a smaller number of indicators and is more meaningful for decision makers. On the other hand, endpoint methods result in more modeling uncertainties than midpoint methods.

4.2.2. *Decision structure*

To increase awareness of the different trade-offs involved in the decision to be made, all of the criteria were placed at the same decision level (Fig. 5). This means that the economic and environmental criteria are compared not only amongst themselves but also between each other,

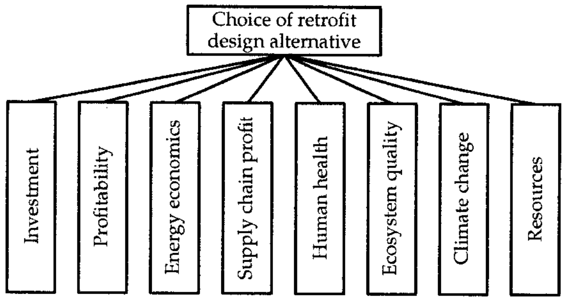

Fig. 5. Proposed decision structure for the retrofit design problem

Table 5
Upper and lower bounds for the economic attributes

Attribute	Upper bound[a]	Lower bound[b]
Capital cost [$]	0	$2.29 \cdot 10^8$
Internal rate of return [%]	20	0
Electrical self-sufficiency [%]	100	0
Supply chain profit [$/y]	$1.25 \cdot 10^8$	0

[a] The utility for the attribute is 1: $u_i(x_i) = 1$
[b] The utility for the attribute is 0: $u_i(x_i) = 0$

Table 6
Upper and lower bounds for the environmental attributes

Attribute	Upper bound[a]	Lower bound[b]
Human health [DALY]	-1077	21
Ecosystem quality [PDF.m^2.yr]	$-2.51 \cdot 10^8$	0
Climate change [kg$_{eq}$ CO_2]	$-1.24 \cdot 10^9$	0
Resources [MJ]	$-1.57 \cdot 10^{10}$	0

[a] The utility for the attribute is 1: $u_i(x_i) = 1$
[b] The utility for the attribute is 0: $u_i(x_i) = 0$

i.e. an economic criterion is also directly compared with an environmental criterion, and vice versa. This avoids comparing an aggregated economic score with an aggregated environmental score, which may lead to an overweighting of the economic objectives of the decision.

4.2.3. *Utility functions*

The utility functions for each of the attributes were scaled by defining a lower bound x_i^{low} and an upper bound x_i^{up} for the attribute values. The lower bound refers to the attribute value for which $u_i(x_i) = 0$ and the upper bound refers to the attribute value for which $u_i(x_i) = 1$. These bounds were chosen for each attribute such that all possible outcomes layed within the range defined by these bounds or were bounded by targets common to the pulp and paper industry (Tables 5 and 6). The utility functions for all of the attributes were assumed to be linear over the complete range. If an attribute value for an alternative was below the lower bound, its utility was set to 0. Likewise, the utility was set to 1 if the attribute value was higher than the upper bound (eq. (2)):

$$u_i(x_i) = \begin{cases} 0 & \text{if } x_i < x_i^{low} \\ mx_i + b & \text{if } x_i^{low} \leq x_i \leq x_i^{up} \\ 1 & \text{if } x_i > x_i^{up} \end{cases} \qquad (2)$$

For the environmental attributes, the lower bound was set as a target defined by performing a life cycle assessment of the Best Available Technologies (BAT). The BAT mill was based on information given by the IPPC (Integrated Pollution Prevention and Control) standards (European IPPC Bureau (2001)). These data were used to determine the changes in environmental impact that would be caused by upgrading the base case mill to the BAT mill standards. Assumptions maximizing the environmental performance were selected in order to represent the best achievable improvement. The upper bound was defined by the worst possible performance based on several scenarios that were run (Janssen et al. (2007a)). Setting these upper and lower bounds guaranteed that all possible attribute values of the design alternatives lie within the range of possible outcomes.

The bounds for the economic attributes were defined by setting their targets. For the upper bound for the capital cost, the maximum value among all the alternatives was chosen. Similarly, the lower bound and target for the capital cost was the minimum value among all the alternatives, i.e. no investment. The upper bound for the IRR was set at a target value of 20%, an acceptable value for the IRR in the pulp and paper industry and the lower bound was set at 0%. The upper bound for the percentage of cogenerated electricity was set at 100% implying complete electrical self-sufficiency, while the lower bound implies no cogeneration at all (0%). Finally, the upper bound and target for the supply chain profit was set at $1.25 \cdot 10^8$ \$/y in order to include the supply chain profit values for all alternatives within the range of the utility function, while the lower bound was set at 0 \$/y because a negative profit is not preferred.

4.2.4. *Weighting*

The trade-off method was chosen as the method to carry out the weighting of the decision criteria which is based on the indifference judgments between alternatives. An indifference judgment determines a trade-off attribute value that makes a decision maker indifferent between two alternatives, i.e. the utility values for these alternatives are equal (eq. (3)):

$$u(A) = u(B) \tag{3}$$

In order to determine the trade-off attribute values for calculating the decision weights, the panel members were first asked to determine the most important decision criterion p. Next, two alternatives A and B, both unrelated to the design alternatives described in section 3, were given that were characterized by the defined criteria and their attributes (Tables 3 and 4) and only differed for two criteria, i.e. the attribute values for the most important decision criterion, x_p and x_q for criterion q were different. The attribute values of these two criteria therefore determined which alternative was more preferred. Assuming additive independence (see eq. (1)), eq. (3) can now be written as:

$$\sum_{\substack{i=1 \\ i \neq p,q}}^{N} k_i u_i(x_i) + k_p u_p(x_p^A) + k_q u_q(x_q^A) = \sum_{\substack{i=1 \\ i \neq p,q}}^{N} k_i u_i(x_i) + k_p u_p(x_p^B) + k_q u_q(x_q^B) \tag{4}$$

$$\Rightarrow k_p u_p(x_p^A) + k_q u_q(x_q^A) = k_p u_p(x_p^B) + k_q u_q(x_q^B) \tag{5}$$

In order to determine the trade-off attribute value x_p^B, alternative A was completely defined, i.e. x_p^A and x_q^A were known. The values for x_p^A and x_q^A were chosen such that $u_p(x_p^A) = 1$ and $u_q(x_q^A) = 0$. For alternative B, only x_q^B was known and $u_q(x_q^B) = 1$. Eq. (5) then reduces to eq. (6):

$$k_p(1 - u_p(x_p^B)) - k_q = 0 \tag{6}$$

Subsequently, the panel members were asked to determine the trade-off attribute value, x_p^B, such that they would be indifferent between alternatives A and B. This was done for each combination of criterion p with one of the other criteria q using eq. (6). Furthermore, the sum of all the weights had to be equal to 1:

$$\sum_{i=1}^{N} k_i = 1 \tag{7}$$

This resulted in a system of N equations with N unknowns and could therefore be solved to obtain the values for k_i (eq. (8)):

$$\begin{pmatrix} 1 - u_p(x_{p,q=1}^B) & -1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 - u_p(x_{p,q=N}^B) & 0 & \dots & -1 \\ 1 & 1 & \dots & 1 \end{pmatrix} \begin{pmatrix} k_1 \\ \vdots \\ \vdots \\ k_N \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix} \qquad \forall q \neq p \tag{8}$$

Next, the overall utility for each of the design alternatives was calculated using the additive formulation (eq. (1)).

4.2.5. *Sensitivity analysis*

Sensitivity analysis was carried out for the trade-off attribute values, x_p^B, determined by the panel members. This sensitivity analysis was done using Monte Carlo analysis as was also proposed by Butler *et al.* (1997). It was implemented in the weight calculation as described in eq. (8). The inputs to the model for this analysis were the probability distributions functions (pdf's) for each value of x_p^B. The average and standard deviation were calculated for each trade-off attribute value. The model assumed that the values of x_p^B were normally distributed and truncated at the lower and upper bounds of x_p^B. A normal distribution $X \sim N(\mu, \sigma^2)$ that is truncated below x_i^{low} and above x_i^{up} results in a truncated normal distribution $Y \sim N(\mu, \sigma^2, x_i^{low}, x_i^{up})$ with:

$$E(Y) = \mu + \frac{\sigma(\varphi_1 - \varphi_2)}{T} \tag{9}$$

$$\sigma(Y) = \sqrt{\sigma^2 \left[1 + \frac{\frac{x_i^{low} - \mu}{\sigma}\varphi_1 - \frac{x_i^{up} - \mu}{\sigma}\varphi_2}{T} \right] - \sigma^2 \left[\frac{\varphi_1 - \varphi_2}{T} \right]} \tag{10}$$

$$T = \Phi(\frac{x_i^{up} - \mu}{\sigma}) - \Phi(\frac{x_i^{low} - \mu}{\sigma}) \tag{11}$$

$$\varphi_1 = \varphi(\frac{x_i^{low} - \mu}{\sigma}) \text{ and } \varphi_2 = \varphi(\frac{x_i^{up} - \mu}{\sigma}) \tag{12}$$

where φ is the probability density function (pdf) with μ the mean and σ the standard deviation of the pdf, and Φ is the cumulative distribution function of a standard normal random variable. Furthermore, x_i^{up} and x_i^{low}, are the upper and lower bounds of the utility functions, respectively. Eqs. (9) to (12) show that truncation leads to different values for the mean and standard deviation of x_p^B.

Table 7
Averages and standard deviations of the trade-off attribute values x_p^B for the decision criteria (n=5)

Decision criteria	Average of x_p^B, μ_{IRR}^B	Standard deviation of x_p^B, σ_{IRR}^B
Profitability	n/a	n/a
Investment	20	0
Energy economics	15.6	0.9
Supply chain profit	15.6	1.3
Human health	15.2	3.9
Ecosystem quality	16.4	4.0
Climate change	17.6	5.4
Resources	18.2	2.4

5. Results & discussion

5.1. *Trade-off valuation*

Profitability was unanimously established as the most important criterion, and therefore all the trade-offs were carried out against the IRR (the attribute for profitability). Not only is profitability important from a strictly economic perspective, also in a social context it is important since a pulp and paper mill, which are often located in remote areas, helps a region to stay economically viable. The value for x_p^A $(p = IRR)$ (see eq. (5)) was thus set at 20% at which $u_{IRR}^A = 1$ for all trade-offs. The closer to 20% the trade-off value, x_p^B, for criterion q is, the less the panel members were willing to give up on the IRR when valued against criterion q (Table 7). For instance, on average the panel members were willing to give up the most on profitability for a decrease of the impact on human health and the least on resources.
The panel members differed more in their opinions concerning the environmental decision criteria. Difficulties in the interpretation of these criteria were an obstacle for determining their value when compared to IRR. Therefore, it was difficult for the panel members to monetize the value of their attributes. Another reason for the larger variance was the difference in opinion between the panel members with environmental background and the ones with a corporate background. The valuation of the human health and ecosystem quality criteria showed this discord based the background of the panel members and explains the large standard deviation. Moreover, only one panel member was willing to trade-off a significantly lower profitability to obtain better performance for the climate change criterion and resulted in an even larger standard deviation. Due to this member's input, the climate change criterion was given some weight. The other panel members argued that there are already financial mechanisms in place which stimulate businesses to reduce their greenhouse gas emissions. These mechanisms thus impact the IRR and make the climate change criterion redundant according to these panelists. In the case of the resources criterion, the same sole panel member was willing to give up on IRR significantly for improving the resources impact, but not to the same extent as for global warming.
The economic criteria showed a lower difference of opinion between the panel members. The trade-off value for capital cost was unanimously set to 20% by the panel members (the upper bound for the IRR utility function), indicating they were not willing to give up any IRR percentage points for a lower capital investment. This trade-off was done between an alternative A with an IRR of 20% ($u_{IRR}^A = 1$) and a capital cost of 229M\$ ($u_{CapEx}^A = 1$), and an alternative B with a capital cost of 0\$ ($u_{CapEx}^B = 1$). It was argued that smaller investment projects are often more risky and therefore require an IRR > 20% according to the panel members. Since the upper bound of the IRR utility function was set at 20%, this value was used to calculate the decision weight for the investment criterion. Electrical self-sufficiency was considered as a means

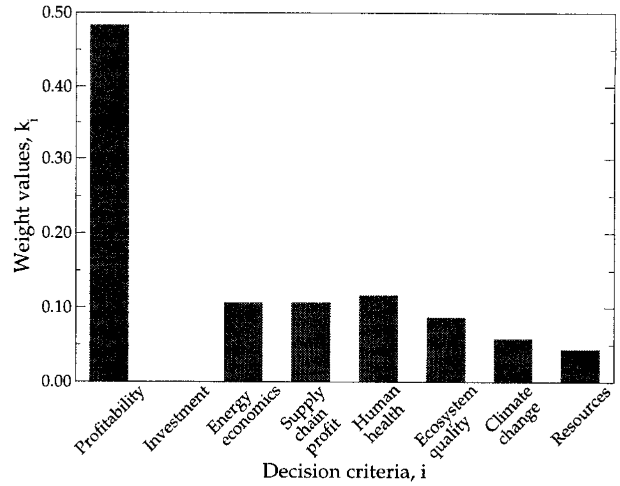

Fig. 6. Decision weighting based on trade-off values

to increase the independence of external energy resources such as natural gas and was therefore considered as a relatively important attribute by all panel members. The panel members were also willing to give up on profitability significantly for an improvement of supply chain profit because supply chain profit was interpreted as a proxy measurement for the survivability of the mill. When a design alternative does not make a profit, then the risk of closing down the mill becomes bigger.

5.2. *Decision weights & overall utilities*

Using eq. (8) and the average trade-off attribute values (Table 7), the weights for each of the criteria were calculated (Fig. 6). The IRR is considered as important as the other decision criteria together and the economic criteria constitute 70% of the total decision weights. The resulting weight for capital cost is 0 because the panel members were not willing to give up any decrease in IRR for a lower capital cost of a design alternative.

Using eq. (1), the overall utilities for the design alternatives were calculated (Fig. 7). All design alternatives were more preferable than the base case mill. This was mostly due to IRR being 0 ($u_{IRR}(0) = 0$) for the base case mill because there were no design changes. Furthermore, capital cost of the base case mill has the most preferred value according to the capital cost utility function, i.e. $u_{CapEx}(0) = 1$, but the decision weight for the investment criterion is 0 (Fig. 6). Alternative 3-B was slightly more preferable than alternative 3-A when using the average decision weights. Alternative 3-B consists of the 100% DIP 1-loop technology, and cogeneration with increased wood waste capacity and a new very high pressure (VHP) steam header. Alternative 3-A also uses the 100% 1-loop DIP technology but has a lower wood waste combustion capacity and has no VHP steam header. Alternative 3-A outperforms alternative 3-B for profitability, but 3-B compensates this by outperforming 3-A in all the other decision criteria (Table 8). This is a result of the better electrical self-sufficiency of alternative 3-B and the resulting economic and environmental improvements. In particular, note that the improved energy economics because of higher electrical self-sufficiency (i.e., higher amount of cogenerated electricity) helps alternative 3-B to become equally preferable to alternative 3-A (Fig. 8). This result suggests that including environmental decision criteria for this case study influences the final design decision. When

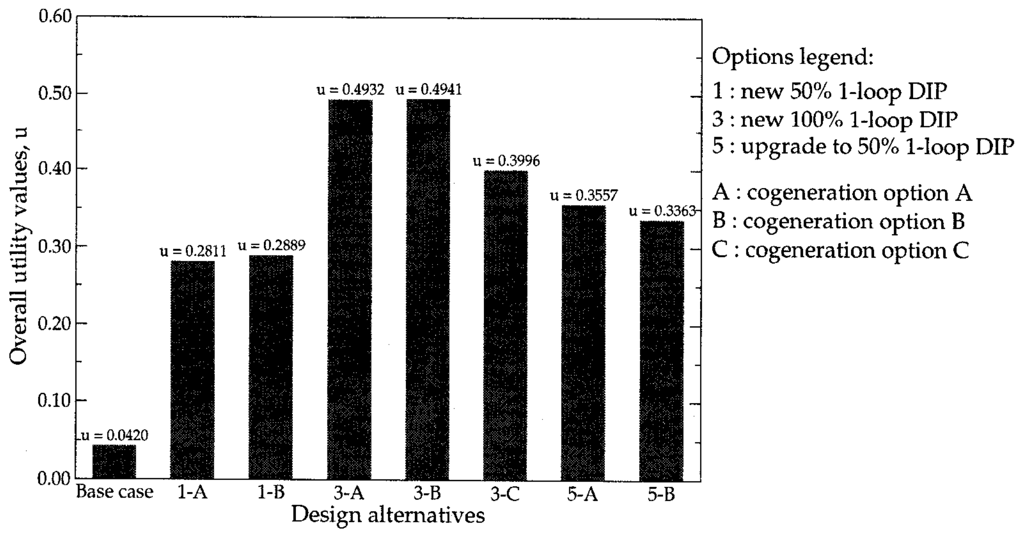

Fig. 7. Utilities for the design alternatives based on the average trade-off values

Table 8
Differences between the attribute values of the decision criteria for alternatives 3-A and 3-B

Decision attributes	Alternative 3-A	Alternative 3-B
IRR [%]	8.1	5.9
Capital cost [$]	$151 \cdot 10^6$	$193 \cdot 10^6$
Electrical self-sufficiency [%]	31.3	56.3
Supply chain profit [$/y]	$107 \cdot 10^6$	$113 \cdot 10^6$
Human health [DALY]	-545	-624
Ecosystem quality [PDF.m^2]	$-1.5 \cdot 10^8$	$-1.7 \cdot 10^8$
Climate change [kg_{eq} CO_2]	$-7.3 \cdot 10^8$	$-8.3 \cdot 10^8$
Resources [MJ]	$-9.5 \cdot 10^9$	$-1.1 \cdot 10^{10}$

only considering the profitability of a design, alternative 3-A would be chosen.

5.3. *Monte Carlo analysis*

The Monte Carlo simulation was run with $1 \cdot 10^4$ iterations and the averages and standard deviations of the trade-off attribute values (Table 7) were used as the parameters for the probability density functions. Upon inspection of the results of the simulation using non-truncated or truncated probability distribution functions, no significant difference in the outcomes were found. The truncated distribution was then used for further analysis, because it better reflects the values that the trade-off attributes may have. Figs. 9 and 10 show the cumulative probability distribution functions for the decision weights and the overall utilities of the alternatives, respectively.

Fig. 9 shows that profitability is always the most important criterion, i.e. there is no overlap with the possible values of the other decision weights. Furthermore, the variation in the trade-off attribute values of the panel members is reflected in the possible values of the decision weights. This variation leads to ambiguity concerning the importance of the criteria, i.e. the importance rank of a criterion may change. The non-dominance of a cumulative probability distribution ac-

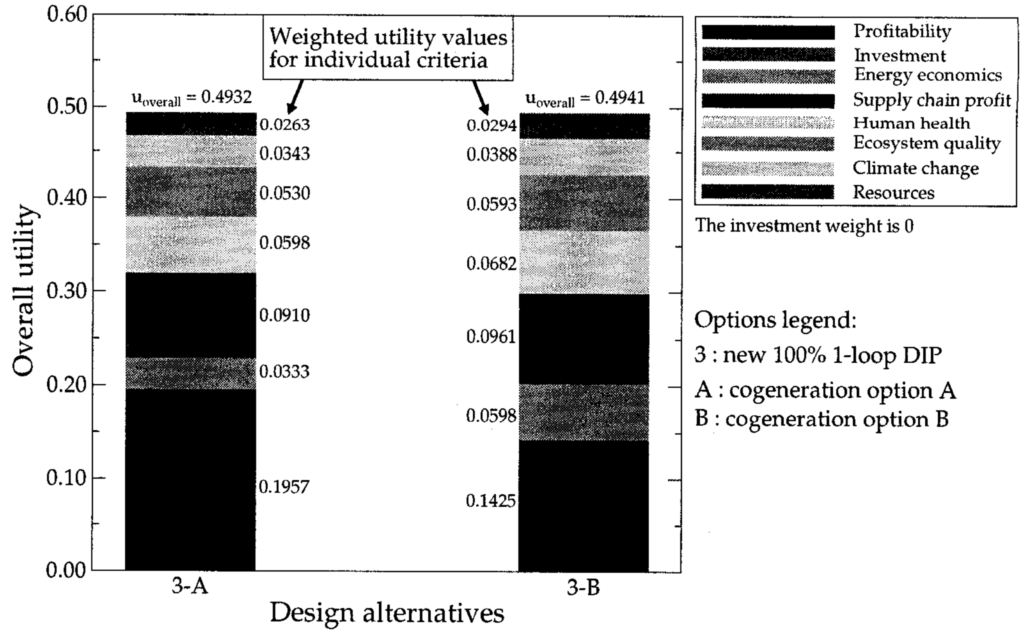

Fig. 8. Comparison of weighted utilities between alternatives 3-A and 3-B split up by criteria

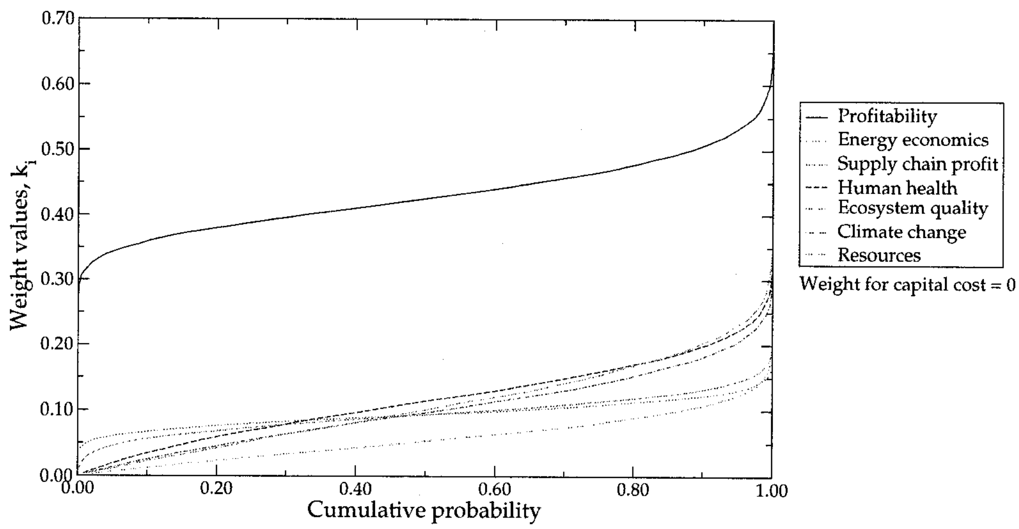

Fig. 9. Results of the Monte Carlo simulation for the decision criteria weights

counts for this ambiguity. Decision weight k_1 dominates decision weight k_2 if decision weight k_1 is always greater than decision weight k_2. For instance, the climate change and ecosystem quality criteria would be less important than the energy economics and supply chain profit criteria in approximately 45% of the possible outcomes.

The outcomes of the overall utility for each design alternative show less ambiguity (Fig. 10). Each

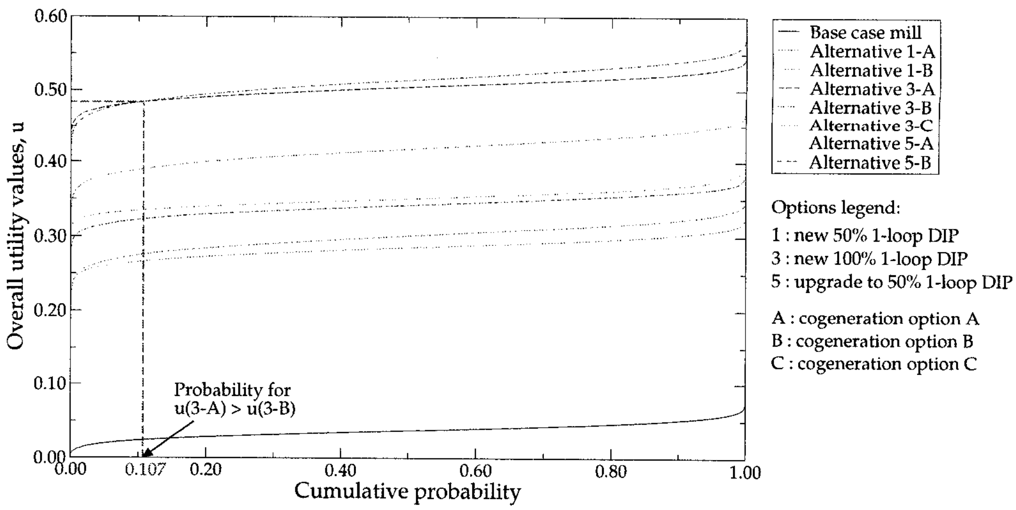

Fig. 10. Results of the Monte Carlo simulation for the overall utility of the design alternatives

cumulative probability distribution for the overall utility of a design alternative is always to the right and below of the preceding distribution, except for the case of alternatives 3-A and 3-B. It shows that in approximately 90% of the possible outcomes alternative 3-B is more preferable than alternative 3-A. Since the overall utilities of these two alternatives based on the average decision weights are very close (Fig. 7), this characteristic helps in making the final decision.

5.4. *Discussion of the decision method*

Before the decision panel was carried out, the decision criteria and their attributes, the utility functions and the decision structure were determined. In order to do this, several choices had to be made related to these elements of the decision method.
The most important choice was the choice of the decision criteria and their attributes. These need to correctly reflect the consequences of choosing a design alternative and thus be able to make the distinction between the alternatives. Both process-level (investment, profitability, energy economics) and supply chain-level (supply chain profit, LCA metrics) criteria were used. During the decision panel it became clear that the members had trouble to interpret the meaning of some of the criteria and attributes, especially the LCA-based criteria. The definition of both the criteria and attributes need to be clear, otherwise it may be hard for a decision maker to interpret these. Furthermore, they thought that some of the criteria were redundant. Not only the climate change criterion (according to four of five members) but also the operating cost and average steam price were considered redundant. The average steam price was proposed as a measure of the energy economics and depends on the fuel mix. As a result, the latter two were not used in the decision analysis. This may be explained by a misconception about multi-attribute utility analysis in the context of engineering design. In traditional design, independence is related to the attributes (x_i) themselves. For instance, the IRR depends on the values of the capital and operating costs. However, in utility analysis, independence is related to preferences for attributes ($u_i(x_i)$) (Thurston (2001)). In other words, in decision analysis the emphasis needs to be put on preference dependence and a decision maker needs to be made aware of that. Furthermore, preferential independence is one of the conditions that need to be satisfied in order to use the

additive formulation for the calculation of the overall utility.
In this work the utility functions were assumed to be linear between pre-set upper and lower bounds (eq. (2)). The shape of the utility functions depends on these bounds and changing these bounds may therefore impact the final decision. The bounds for the environmental criteria were based on a life cycle assessment of the BAT (Best Available Technologies) mill and scenario analysis and thus were based on accepted engineering practices. The economic criteria however were more difficult to determine. Especially the upper bound for the IRR, which was also the target value, was prone to discussion. Initially it was set at 12%, but based on remarks of the panel members with a corporate background, it was raised to 20%. This indicates that the investment policies in the pulp and paper industry are conservative. Utility functions may also assume different shapes, often exponential functions are used for describing the preferences of a decision maker. More specifically, the shape indicates the risk behaviour of the decision maker towards an attribute. A convex function represents risk prone behaviour, a concave function risk averse behaviour and a linear function suggests risk neutral behaviour (Keeney and Raiffa (1976)). In this case study, using the decision weights that were determined by the panel members, overall risk prone behaviour would favor alternative 3-B.
Instead of trading off an overall environmental and economic score, based on the separate environmental and economic criteria respectively, the decision structure that was used put all the criteria at the same decision level. When one aggregated environmental criterion is used, it is usually given a very small weight compared to economic criteria (see e.g. Duarte *et al.* (2001)). This is due to the fact that environmental improvement is mostly initiated by setting regulation and thus considered as a constraint on the operation of a mill instead of as an objective. In this instance, the decision structure resulted in a 70:30 split of the weights between the economic and environmental criteria. This suggests that using this decision structure took better into account the different viewpoints of the panel members and raised their awareness about the others' opinions through the discussions. These discussions about the trade-offs between IRR and the environmental criteria and the resulting variation in the trade-off attribute values also highlighted the difficulty of monetizing the environmental criteria.

6. Conclusions

This paper presented a method for multi-criteria decision making for retrofit process design using process- and supply chain-level criteria. Compared to the decision process used in traditional retrofit process design, the current decision method is better able to consider multiple objectives in order to come to a more balanced final decision. The traditional design decision making process only uses an economic objective that is subject to environmental regulations, whereas this method also uses environmental objectives. The use of available data and process systems engineering tools results in a diverse set of decision criteria that enable a more broad perspective on the decision problem. Subsequent Monte Carlo analysis is able to refine the outcomes of the decision analysis.
It is important to communicate about the decision criteria and the attributes. In order to guarantee clarity of the criteria and attributes, key design parameters need to be identified and discussed with the decision makers as part of the decision panel. These parameters may also include risk- or sensitivity-based criteria to account for e.g. price volatility and long term risks, product marketability (is there an opportunity to enhance product sales or price as a consequence of a retrofit design of the existing manufacturing process and subsequently, raw materials used), safety, technological risk and social criteria such as public acceptability or worker headcount. Furthermore, the risk behaviour of the decision makers needs to be taken into account through discussion and determination of the shape of the utility functions.

The results of the case study indicate that the use of multiple criteria can alter the final decision. Not only profitability was a deciding factor, also the level of electrical self-sufficiency and the resulting environmental benefits had a deciding impact on the outcome of the decision analysis.

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A.5 Retrofit process design methodology for sustain-abillity

Retrofit process design methodology for sustainability

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Abstract

This paper presents a new methodology for retrofit design decision making using process and cost data available from Information Management Systems and process systems engineering tools. This methodology consists of three major steps. First, a set of design alternatives and the existing design are characterized at the process level using a new operations-driven cost modeling approach. Second, the obtained process and cost information is used in a supply chain-level analysis that uses Life Cycle Assessment and supply chain models in order to deduce the impact the design changes may have at this level. Third, a multi-criteria decision making panel is carried out in order to evaluate and select the most preferred design alternative based on process- and supply chain-level decision criteria. A case study demonstrates that this methodology results in consistent use of the same data at both analysis levels, and leads to a more sustainable design decision.

Introduction

The Canadian pulp and paper industry currently faces many challenges. Competition from mills in countries with low production costs and advantageous economies-of-scale, the increasing price of energy, larger fibre costs and currency exchange rates, amongst others, are making it increasingly more difficult for Canadian pulp and paper companies to survive in the global market place. Moreover, due to its energy-intensive nature, the industry has a large environmental footprint that needs to be dealt with. This requires the industry to re-think its strategic goals and consider sustainability as a new basis for competitiveness.

The Brundtland commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [1]. More recently, there has been a growing market demand for sustainability benchmarks. For instance, the Dow Jones Sustainability Indexes (DJSI) were launched in 1999 in order to track the financial performance of leading sustainability-driven companies worldwide [2]. The DJSI show that sustainability performance is advancing, but there is still room for improvement [3]. Pulp and paper companies do not have a prominent place in the DJSI, indicating that the sustainability of the industry is not yet world-leading, although industry initiatives were started in order to address sustainability [4].

The implementation of Data and Information Management Systems (DMS and IMS, respectively) at pulp and paper mills have made available massive amounts of process, cost and environmental data. The effective use and availability of these data have increased insight in the production and business processes at pulp and paper mills. It has also been established that

these data have not been fully exploited and as such, there is room for improvement [5]. Retrofit process design is one of the fields that may benefit from improving the use of the available data with Process Systems Engineering (PSE) tools.
A framework for retrofit design decision making was presented by Janssen & Stuart [6] that proposed the combination of PSE tools that consider the supply chain level, i.e. LCA and supply chain models, with tools that are situated at the process level. This article further details the use of this framework in the context of design for sustainability. First, previous work on process design for sustainability is reviewed and the design case study is described. Then, a detailed description of the methodology is given for implementing the aforementioned design decision framework. Next, the results of applying the methodology using the case study are discussed, followed by conclusions.

Process design for sustainability

The concept of sustainability consists of three dimensions: an economic, an environmental and a social dimension. Traditionally, in chemical process design, only economic objectives have been considered for decision making and the environmental and social aspects of process design have been used as constraints (see e.g. [7, 8, 9, 10]). Nevertheless, many companies claim to have adopted sustainable business practices in order to enhance reputation, competitive advantage and cost savings. Design for sustainability is one of those business practices that can contribute to tangible financial value, intangible assets (e.g. reputation, human capital, innovation) or value for stakeholders [11].
Considering sustainability in process design or optimization offers many opportunities for the application of process systems engineering [11]. Since sustainability is a property of an entire ecosystem, and not only a property of an individual subsystem such as a production plant, the system boundaries need to be expanded outside a plant's or even a corporation's boundaries. Furthermore, considering sustainability requires that the boundaries of analysis include socio-economic-ecological aspects. Also, the quality of data from different sources needs to be ensured through reconciliation as is the case when using of process and cost data available from IMS.
Another important point in the use of sustainability for design purposes is how to measure it. Sikdar [12] discussed types of metrics for sustainability and made the distinction between the use of aggregate metrics and one-, two- and three dimensional metrics (based on the three dimensions of sustainability). The three-dimensional metrics would fully reveal the sustainability features, whereas the one- and two-dimensional metrics would help to further elaborate for decision making. The consolidation of these separate metrics in aggregate metrics, which would provide an overall measure for sustainability, is difficult and would need the valuation (e.g. monetization) of these metrics. This may be accomplished using multi-criteria decision analysis.
Most applications in the chemical engineering literature have focused on the trade-off between economic and environmental performance when considering sustainability during process design. Some approaches used LCA to expand the environmental perspective of the design problem but considered economics at the plant level [13, 14, 15]. Hugo & Pistikopoulos [16] included supply chain aspects in order to also expand the economic perspective from the plant level to the supply chain level. Sofar, the applications that consider sustainability for process design using LCA and/or supply chain modeling have mostly been for greenfield design. There are numerous other examples in the literature that consider both economic and environmental objectives, but these did not systematically consider the complete product life cycle for design or optimization by using LCA and/or supply chain modeling. Rather, these applications used *ad hoc* metrics that reflect the sustainability of a design (e.g. Zhou *et al.* [17]). Azapagic *et al.* [18] proposed a

methodology that integrates sustainability into process design and considered the product life cycle and complete design cycle, from project initiation to final design. In this methodology, all three sustainability dimensions were represented, but were not integrated into one overall sustainability metric. This methodology also focused on greenfield process design and did not consider supply chain aspects.

Greenfield or retrofit process design for sustainability is still a largely unexplored field in the pulp and paper industry. As one example, Cornejo *et al.* [19] used an aggregate environmental metric, composed of the weighted sum of LCA and EIA (Environmental Impact Assessment) metrics, and the Net Present Value (NPV) to compare retrofit design alternatives during the preliminary design phase. However, the LCA that was carried out was a gate-to-gate LCA and thus considered only the environmental impact of the plant. To the authors' knowledge, the supply chain level, considering both the environmental and economic dimension, has not been included in process design in this industry.

Objectives

The objectives of this paper are:

- To elaborate a new methodology for retrofit design decision making that makes use of process and cost data available from information management systems and process systems engineering tools
- To demonstrate the use of the methodology for making more sustainable design decisions using process- and supply chain-level decision criteria
- To apply this methodology to a retrofit design case study situated at an integrated newsprint mill that focuses on energy and fibre use.

Case study description

Newsprint production is an energy-intensive process because it requires large amounts of steam and electricity. Steam is produced in a boiler plant by burning fossil fuel and/or biomass. Thermo-mechanical pulp (TMP) production requires large amounts of electricity due to its consumption by the TMP refiners. The refiners process wood chips to produce wood fibre and, as a by-product, low grade steam. A number of techniques have been available to reduce the electricity consumption of the refiners but they yield only marginal gains in electricity use. On the other hand, a de-inked pulp (DIP) plant uses waste paper to produce fibre and uses much less electricity per tonne of fibre produced than a TMP plant. In this context, partly or completely replacing TMP pulp production with increased production of de-inked pulp will dramatically affect the mill-wide energy consumption. Also, due to an increase of steam production in the mill's boiler plant to compensate for the decrease or absence of steam production in the TMP plant, the increase of DIP pulp production can give rise to a potential opportunity for cogeneration by existing or newly implemented turbines. The case study in this work therefore considers the implementation of increased de-inked pulp production and cogeneration at an integrated newsprint mill.

The flow diagram and main in- and outputs of the base case mill are given in Figure 1. The mill produces 1100 tonnes/day of newsprint paper on four paper machines, and uses 925 tonnes/day of TMP pulp and 175 tonnes/day of DIP pulp (for more detailed information on the base case mill, see [20]).

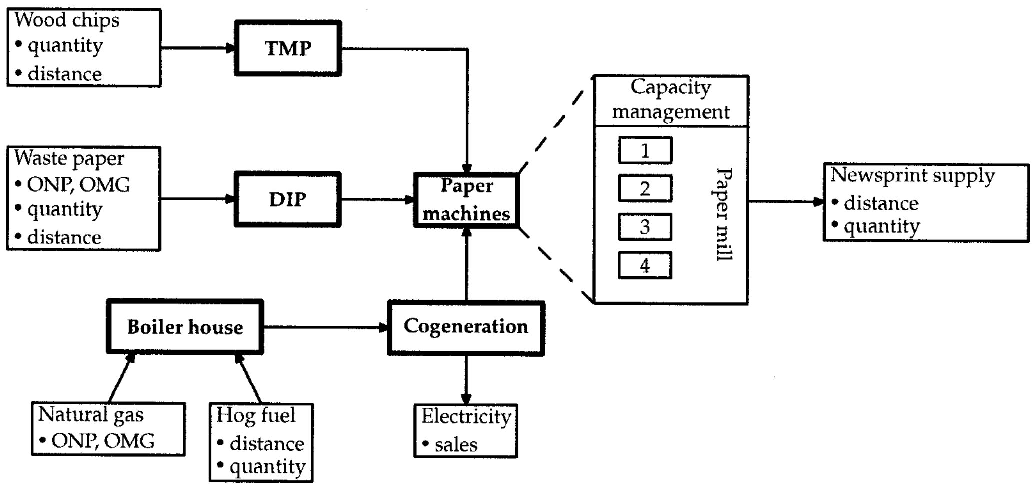

Figure 1: Flow diagram of the base case mill process and main inputs and outputs

Table 1: DIP plant configurations

Option	Configuration
1	New 550 tonnes/day DIP plant, 1-loop
2	New 550 tonnes/day DIP plant, 2-loop
3	New 1100 tonnes/day DIP plant, 1-loop
4	New 1100 tonnes/day DIP plant, 2-loop
5	Increase to 550 tonnes/day by adding a second line to the existing plant, 1-loop
6	Increase to 550 tonnes/day by adding a second line to the existing plant, 2-loop

De-inking and cogeneration configurations

The DIP plant retrofit design configurations consider a production of 550 tonnes/day or 1100 tonnes/day (representing a 50% or 100% DIP integrated newsprint mill, respectively) (see Table 1). Both the 1-loop and 2-loop DIP technologies are considered. A 1-loop DIP system is a system that processes the recycled paper in one alkaline cleaning stage. A 2-loop system has an additional second cleaning loop that operates under acidic conditions making it a more rigorous cleaning process. The 1-loop DIP plant configuration has a lower capital cost when compared to a 2-loop system with the same capacity. On the other hand, a 2-loop configuration provides more rigorous cleaning technology. The cogeneration configurations increase the wood waste capacity of the boilers and reactivate currently idle equipment, and have newly implemented back-pressure or condensing turbines (see Table 2 and Figure 2).
In total, 18 alternatives were analyzed in this case study by considering all possible combinations of the DIP and cogeneration configurations. The following naming convention for the design alternatives was used: Alternative {DIP configuration 1 to 6 as per Table 1}-{Cogeneration configuration A, B, or C as per Table 2}.

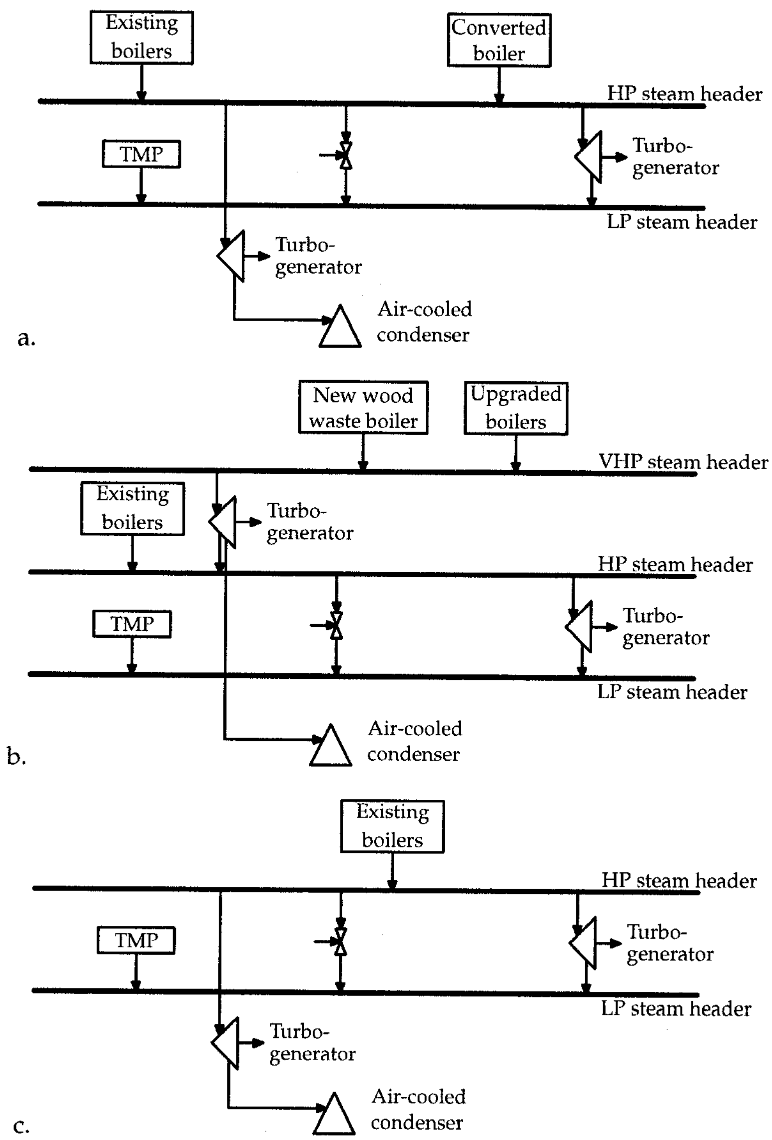

Figure 2: Cogeneration configurations: a. configuration A, b. configuration B, and c. configuration C

Table 2: Cogeneration configurations

Option	Configuration
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines are kept in service
B	New wood waste boiler (at very high pressure (VHP)) is installed. Half the boilers are upgraded to VHP operation. New backpressure turbine is added to existing ones
C	New air-cooled condenser and condensing turbine are installed

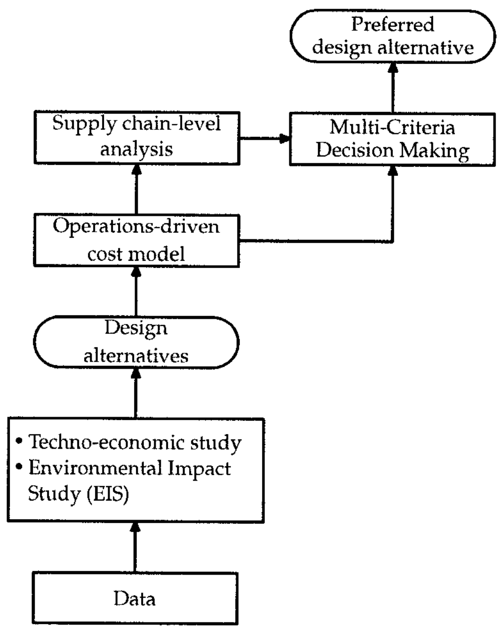

Figure 3: Overall methodology of the new retrofit design approach

Overall methodology

The new methodology consists of three parts (Figure 3). It is based on a bottom-up approach of using process and cost data available from Information Management Systems (IMS) at an integrated newsprint mill. The idea is to first characterize operation of the existing design and the retrofit design alternatives at the process level and then use the obtained process information at the supply chain level in order to obtain information about changes in supply chain operation, and about the environmental impact of the design alternative at this level. This information is subsequently used for design decision making.

Characterization at the process level

First, a techno-economic study is carried out in order to generate the retrofit design alternatives. The manufacturing costs are then modeled for each alternative using a novel operations-driven cost modeling approach that is based on:

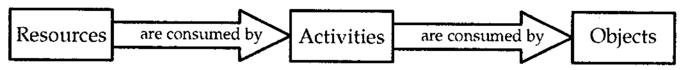

Figure 4: Relationship between resources, activities, and objects in ABC

- Process design characterization using mass and energy balances
- Activity Based Costing-like (ABC-like) accounting principles.

ABC is a cost system that first accumulates overhead costs for each of the activities of an organization, and then assigns the costs of activities to the products, services, or other cost objects that caused that activity [21]. Furthermore, it allows modeling of the usage of resources by the activities that are carried out, followed by linking the activities with the cost object (Figure 4). In this case, the cost object is the newsprint paper product. The consumption of resources by activities is quantified by a resource driver and the consumption of activities by objects is quantified by an activity driver. Both kinds of drivers are determined by using process information. ABC has a more process-oriented approach for tracing costs than the traditional volume-based costing method. Besides this, ABC also leads to higher accuracy, results in better allocation of overhead costs and is able to provide better performance indicators [22, 23, 24, 25, 26, 27].
The operations-driven cost modeling approach applied to retrofit design consists of four steps (Figure 5) and is completely implemented in the Impact:EDC^{TM} software by 3C Software:

① Calculation of total capital costs for each design alternative

② Calculation of mass and energy balances for each design alternative

③ Modeling and calculation of manufacturing costs for the design alternatives and operating variants

④ Calculations for the evaluation of the design alternatives and operating variants.

The operations-driven cost model is used to calculate the manufacturing cost per tonne of newsprint. Process and Overhead Work Centres (*PWC* and *OWC* respectively) are defined to represent the production departments of the mill and the resources are linked to them (Figure 6). The *PWC*s accommodate the cost flow along the process, the design criteria and characteristics of each alternative and their operating variants, calculations specific to each *PWC*, the assignment of overhead costs, and finally, the cost calculation that is based on ABC-like principles. The *OWC* calculates the overhead costs using allocation base information.
Using profitability metrics, a set of design alternatives is retained. The retained design alternatives are then analyzed in more detail by carrying out marginal cost analysis. In particular, the marginal steam cost, $C^{marg,steam}$, is calculated using equations (1) and (2):

$$C^{marg,steam} = \frac{C_q^{steam,tot} - C_{q-1}^{steam,tot}}{P_q^{steam,tot} - P_{q-1}^{steam,tot}} \tag{1}$$

and:

$$C_q^{steam,tot} = P_q^{steam,tot} p_q^{steam} \tag{2}$$

where $C^{steam,tot}$ is total steam cost [$], $P^{steam,tot}$ is total steam produced by the boiler plant [GJ] and p^{steam} is the average steam price (cost) [$/GJ]. The steam price is based on the fuel mix used, which consists of wood waste, sludge produced by the DIP and waste water treatment plants

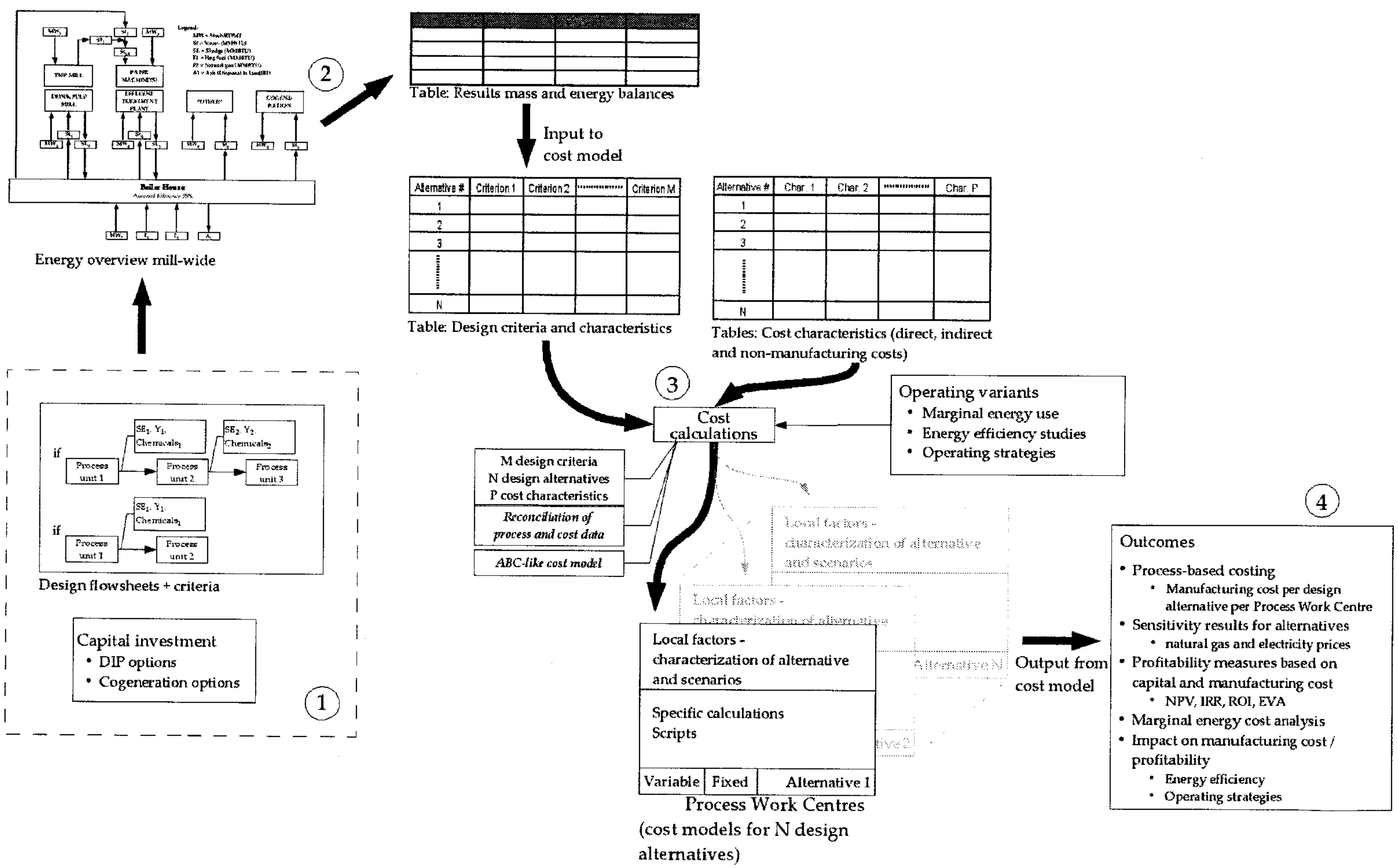

Figure 5: Implementation of the operations-driven cost modeling approach for retrofit process design:① capital cost calculation,② mass and energy balances,③ cost model,④ design evaluation

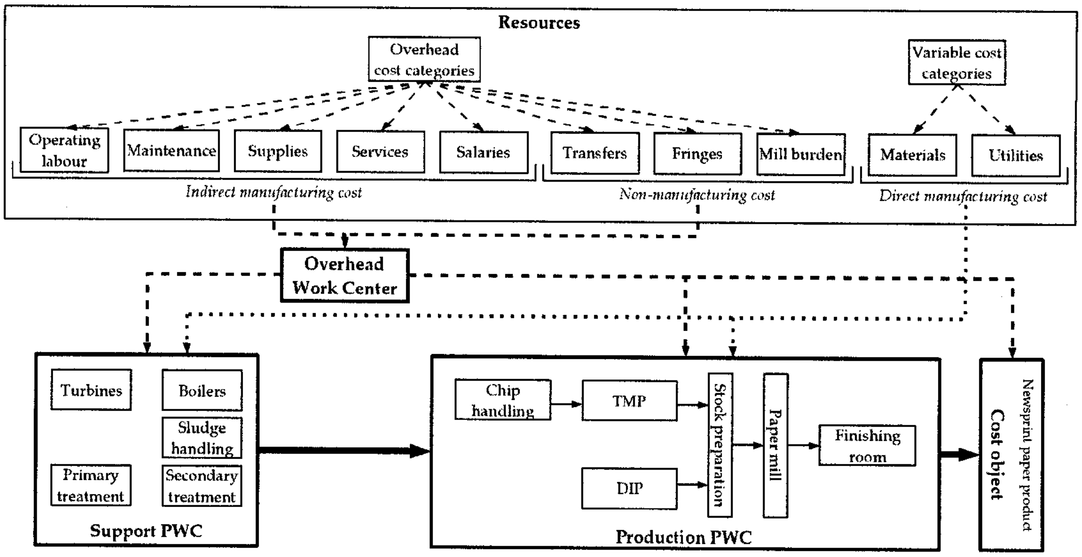

Figure 6: Cost categories at the case study mill and definition of Process and Overhead Work Centres (*PWC* and *OWC*)

and natural gas.
Furthermore, this approach can be used to carry out profitability analysis for energy efficiency studies or for assessing the impact of operational strategies. The focus in this paper will however be on the marginal cost analysis.

Supply chain-level analysis

The next step in the methodology is to use the cost and production information gathered with the operations-driven cost model in a supply chain-level analysis (Figure 7). This bottom-up approach to using the process and cost data therefore first considers the retrofit design changes at the process level, followed by the inclusion of supply chain level considerations. This analysis is carried out using:

- A supply chain model that is developed in order to consider the impact of changing market conditions on the mill and supply chain operations using scenario analysis. This model is implemented in MS Excel using the Solver add-in [28].
- A Life Cycle Assessment (LCA) model that is developed in order to determine the environmental impact under those same market conditions at the supply chain level. The LCA model is implemented using the SimaPro software by PRé Consultants.

This is done for all of the retained design alternatives.
The supply chain model maximizes the annual supply chain profit. It uses production information generated by mass and energy balances in order to characterize the manufacturing operations of the alternatives. The cost information it uses consists of the unit resource costs to calculate the raw material (wood chips, waste paper, wood waste and natural gas), supplies, chemicals and electricity costs. Furthermore, the overhead costs are taken into account in the model and adjusted where necessary.
On the other hand, the LCA model uses only the production information and characterizes the

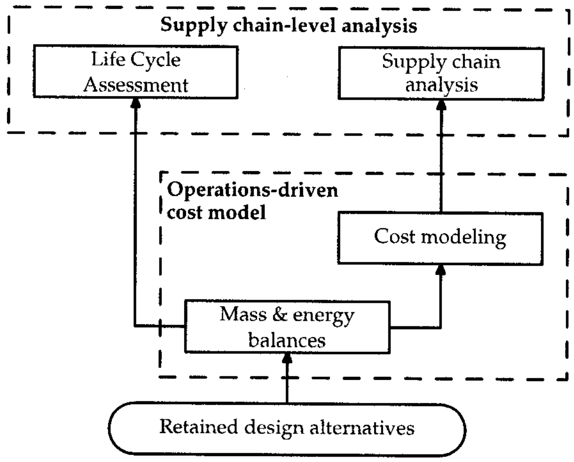

Figure 7: Use of information generated by the operations-driven cost model in the supply chain-level analysis

environmental impact of the alternatives. The material flows that are expected to show significant changes are selected and the information is extracted from the cost model. The LCA model used calculates the environmental impact changes of the retrofit design alternatives compared to the base case mill. Since the operations-driven cost model is supplying only mill process data, it is necessary to complete these data with the most appropriate generic data for non-mill processes that characterize the other parts of the life cycle. The impact assessment is carried out using the IMPACT 2002+ characterization method [29]. This method characterizes the environmental impact using four categories: human health, ecosystem quality, climate change and resources. Besides the LCAs for the alternatives, there is also one done for the BAT (Best Available Technologies) mill. The BAT mill is based on information given by the IPPC (Integrated Pollution Prevention and Control) standards [30].

Multi-Criteria Decision Making (MCDM) panel

The last step in the overall methodology is carrying out a Multi-Criteria Decision Making (MCDM) panel. The panel evaluates the design alternatives based on a set of environmental and economic decision criteria that are calculated using the operations-driven cost and supply chain-level models. The MDCM panel may be considered a proxy for the interplay that takes place in a company for approval of large-scale retrofit projects. The decision method employed is based on Multi-Attribute Utility Theory (MAUT) [31]. Attributes characterize or quantify the decision criteria, e.g. the attribute for profitability of a design alternative can be the return on investment. Utilities are a measure of preference and can be used when the decision maker does not exactly know the consequences of a decision that will be made. Therefore, MAUT is suitable for decision making under uncertainty. Using MAUT, two attribute characteristics need to be determined:

- The preference the decision maker has for a range of attribute levels
  This is done by determining the utility function $u_i(x_i)$ for criterion i over a range of values for an attribute x_i. This can therefore be characterized as an *intra*-comparison of preference for attribute levels.

- The importance of an attribute compared to the other ones.

This is done by determining the weight k_i of an attribute for criterion i. This is characterized as an *inter*-comparison of importance between attributes.

The most common formulation of the (overall) multi-attribute utility function is the additive utility function, which requires that the utilities are additively independent:

$$u(x) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{3}$$

with: $\sum_{i=1}^{N} k_i = 1$ and $0 \leq k_i \leq 1$, where $u(x)$ is the multi-attribute utility function and N the number of criteria. This formulation is used to calculate the overall utilities for the retained design alternatives.
The utility functions, $u_i(x_i)$, are assumed to be linear between an upper and lower bound, x_i^{low} and x_i^{up} (eq. (4)):

$$u_i(x_i) = \begin{cases} 0 & \text{if } x_i < x_i^{low} \\ mx_i + b & \text{if } x_i^{low} \leq x_i \leq x_i^{up} \\ 1 & \text{if } x_i > x_i^{up} \end{cases} \tag{4}$$

These bounds, are chosen for each attribute such that all possible outcomes lay within the range defined by these bounds or are bounded by targets. More specifically, for the environmental attributes, the targets are set by the outcomes of the LCA of the BAT mill. The bounds for the economic attributes are defined by setting their targets.
The task of the panel is to establish the decision weights of each of the criteria, i.e. the importance of each of the criteria. This is done using the trade-off method [32]. This method is based on indifference judgments between alternatives by the panel members. An indifference judgment determines a trade-off attribute value that makes a decision maker indifferent between two alternatives. Using this method, the panel members first need to establish the most important decision criterion and then trade off each of the other criteria against this one. Knowing that the multi-attribute function is given by equation (3), all k_i can then be determined and subsequently the overall utility, $u(x)$, for each design alternative based on the average trade-off values of the panel members. Finally, a sensitivity analysis of the trade-off values is carried out by employing a Monte Carlo analysis [33]. It is assumed that the trade-off attribute values are normally distributed and truncated at the lower and upper bounds of their utility functions. The Monte Carlo simulation is run with $1 \cdot 10^4$ iterations.

Results and discussion

Process-level characterization

Capital & manufacturing costs

The total capital cost estimate for each of the design alternatives was obtained by addition of the estimates for the DIP and the cogeneration options (Figure 8). The 100% 2-loop DIP alternative with cogeneration option B had the highest capital cost at \$229 million, whereas the 50% 1-loop DIP upgrade alternative had the lowest capital cost at \$87 million.
The direct and overhead manufacturing costs were calculated per *PWC* for each alternative (Figure 9). A negative value for a *PWC* cost indicates that this work centre either has a net positive income or transferred costs to outside the paper mill. The cogenerated electricity is sold to the grid with an assumed 50% premium over the nominal electricity price, making the Turbines

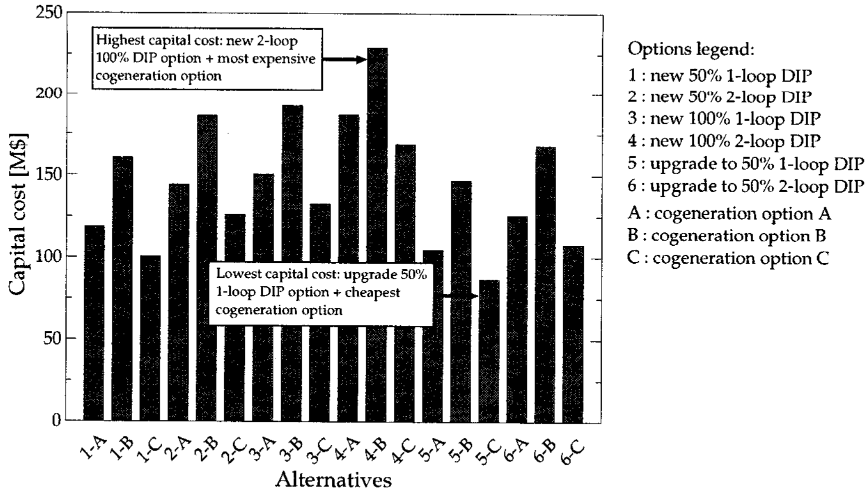

Figure 8: Capital costs of the design alternatives

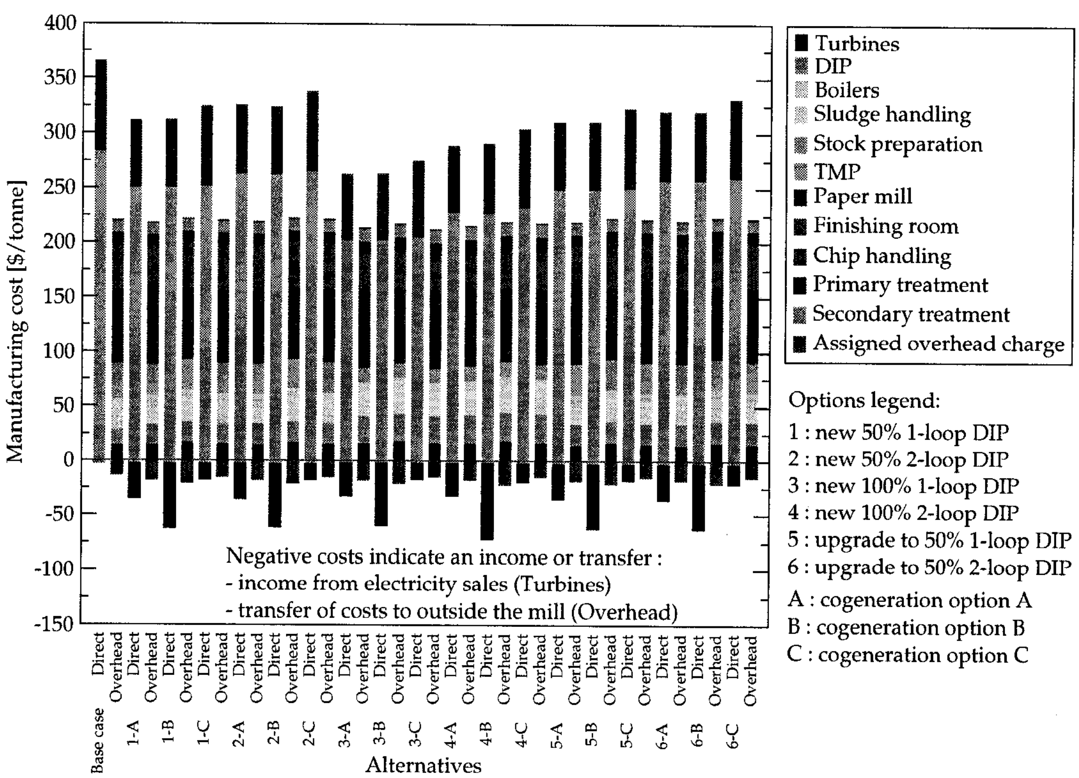

Figure 9: Manufacturing costs of the design alternatives split by Process Work Centre and by direct and overhead costs

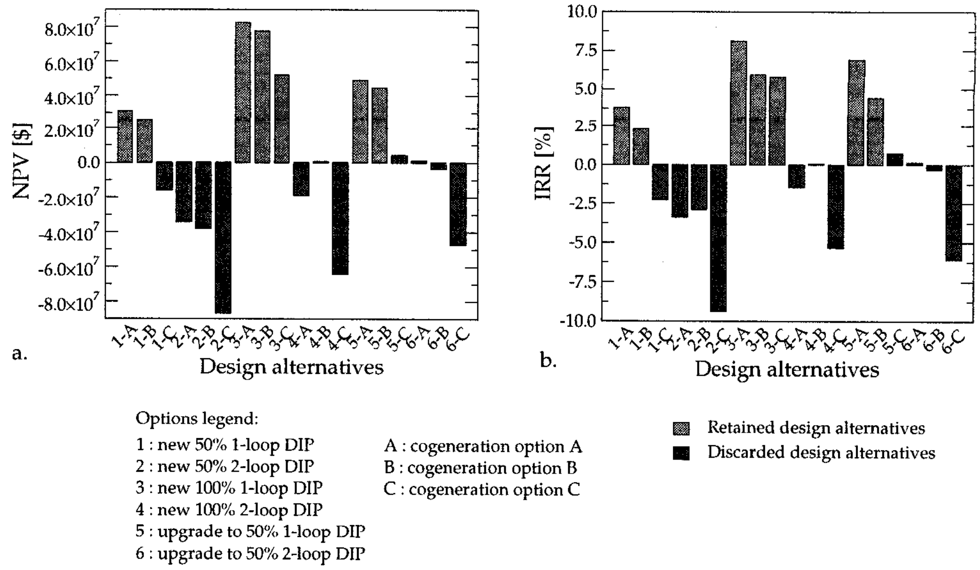

Figure 10: Profitability of the design alternatives: a. NPV; b. IRR

PWC an important profit centre for the alternatives. The cost of fibre is the most significant cost for the TMP and DIP plants, and varies with changes in furnish to the paper machines, i.e. whether the percentage of DIP pulp in the furnish is 50% or 100%. Furthermore, differences in yield and steam use between the 1-loop and 2-loop DIP configurations create a difference.
The base case mill and the alternatives with cogeneration option C have lower wood waste capacities in their boiler plants and therefore use more natural gas to meet process steam demand. The increased costs due to higher natural gas use are assigned to the *PWC*s that use this steam because of the operations-driven nature of the cost model. The cost model thus links the resources used and their costs to the activities in each *PWC*, in this case steam use, and brings process and business knowledge closer together.

Profitability analysis

Profitability analysis reveals that ten alternatives should be retained using IRR > 0 as the screening criterion including the three 100% 1-loop DIP design alternatives (Figure 10). However, three of these alternatives are discarded because they have only marginal profitabilities and therefore seven alternatives are considered for further analysis. Alternative 3-A, a 100% 1-loop DIP alternative, is most profitable at an IRR of 8.1% (and an NPV of $82.3 million).

Electrical self-sufficiency

Electrical self-sufficiency, defined as the percentage of the mill electricity demand that is fulfilled by the cogenerated electricity, was calculated based on the mass and energy balances (Figure 11). The cogeneration potential of alternatives 3-A and 3-B (both 100% 1-loop DIP alternatives) nearly double when compared to their 50% DIP 1-loop counterparts (alternatives 1-A, 1-B, 5-A and 5-B). This is due to the decrease in the electricity demand of the 100% DIP alternatives because the TMP plant is shut down. All retained design alternatives have a much higher electrical self-sufficiency than the base case mill because in all cases the mill electricity demand is lower and

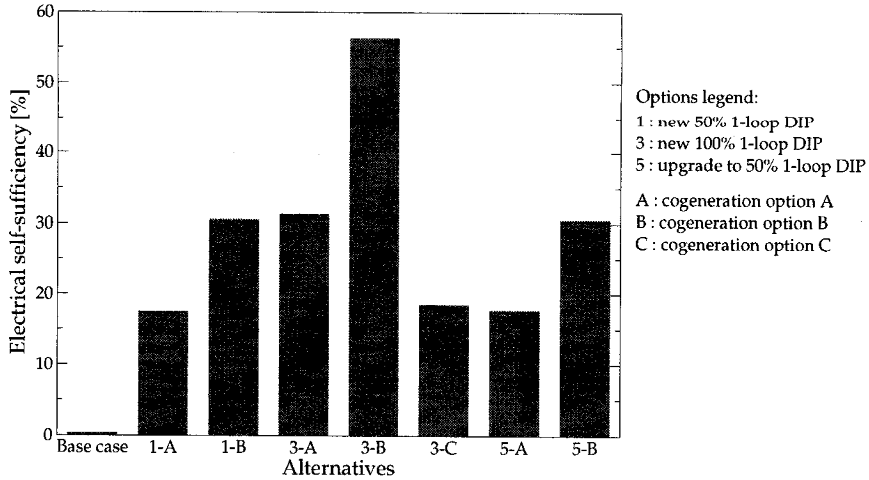

Figure 11: Electrical self-sufficiency of the retained design alternatives and the base case mill

the amount of cogenerated electricity is higher.

Marginal cost analysis

The marginal steam cost demonstrates the impact of changing the fuel mix for increased steam production (Figure 12a). The marginal steam cost is lower than the average steam cost when increased steam production results in increased wood waste use only for the alternatives with cogeneration options A and B. After natural gas is added to the fuel mix, the marginal steam cost is higher than the average steam cost. Therefore, these alternatives should not produce any incremental steam using natural gas because they then will lose money. For instance, the average steam cost in alternative 3-A is \$2.15/GJ when it starts to use natural gas, whereas the marginal cost is \$10.50/GJ. As a result, an incremental GJ of steam produced is \$8.35 more expensive. On the contrary, at full wood waste capacity, the average steam cost is \$1.95/GJ and the marginal steam cost is \$1.45/GJ which indicates that an incremental GJ of steam produced is \$0.50 cheaper. Only alternative 3-C does not display a jump in the marginal steam cost. Natural gas is already the marginal fuel at the minimum steam production rate that satisfies the demand for this alternative due to its lower wood waste capacity. This results in a marginal steam cost higher than the average steam cost at all steam production rates.

Alternatives with cogeneration options A and B reach optimal profitability when wood waste use is maximized and natural gas use minimized (Figure 12b). These are the operating conditions under which the initial profitability analysis was done (Figure 10). These results reflect the outcomes of the marginal energy cost analyses, i.e. these alternatives would start to lose money as soon as they would use natural gas.

The marginal steam cost analysis is readily implemented in the cost model because the model focuses on the activities that take place in the process units (or *PWCs*), e.g. steam production in the boiler plant. Consequently, changes in these activities lead to changes in resource use which leads to changes in the manufacturing costs.

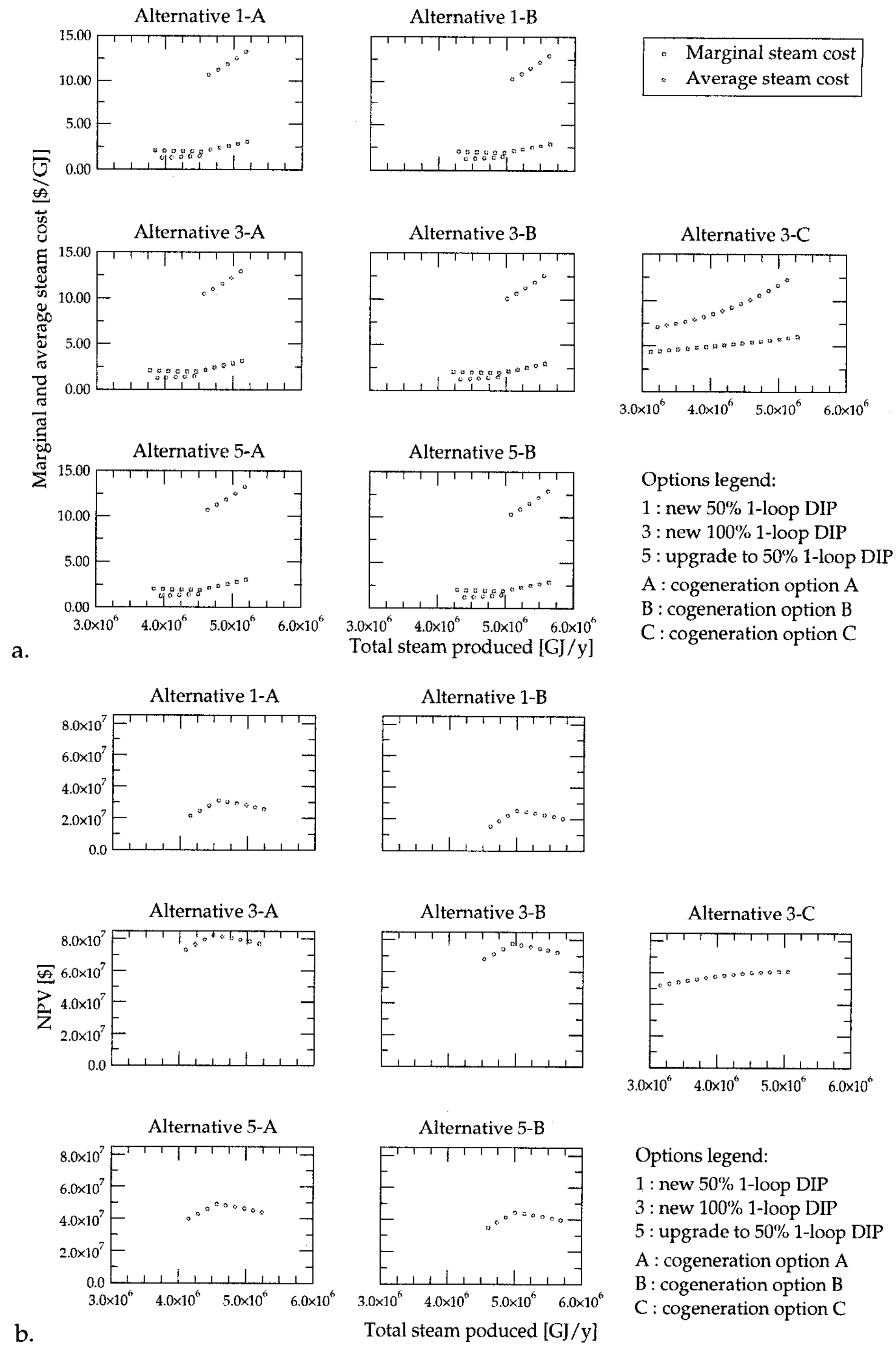

Figure 12: Marginal cost analysis of the retained design alternatives: a. marginal and average steam cost, b. profitability change

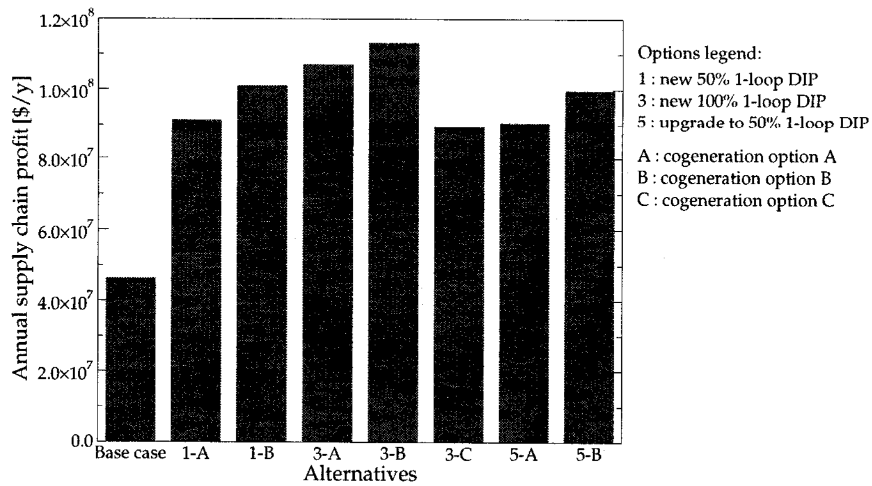

Figure 13: Annual supply chain profit for the retained design alternatives and the base case mill

Supply chain-level analysis

The annual supply chain profit and environmental impact improved for all alternatives compared to the base case mill (Figures 13 and 14). The difference in supply chain profit between the alternatives is mostly due to the difference in the amount of electricity cogenerated. Furthermore, note that the design alternative with the highest profitability (Figure 10) does not have the highest supply chain profit: alternative 3-B has the highest annual supply chain profit, whereas alternative 3-A is most profitable. Alternative 3-B achieves a higher profit due to the higher income it gains from selling cogenerated electricity, but has a lower profitability because it requires a higher investment (Figure 8). The increase in environmental performance of the alternatives is mostly due to reduced TMP pulp production (50% DIP alternatives) or shutdown of the TMP plant (100% DIP alternatives) and the increase of cogenerated electricity. Consequently, alternative 3-B outperforms all other alternatives for each impact category, because the TMP plant is shut down and cogeneration option B has the biggest electricity generation capability.

The supply chain-level analysis results in the identification of an alternative (alternative 3-B) that outperforms all other alternatives at this level based on the metrics that are employed. Based on this analysis alone, this suggests that alternative 3-B is the most sustainable alternative, since the inclusion of the supply chain level enlarges the system's boundaries beyond the process level and thus considers a more encompassing system [11]. Furthermore, the approach taken first considers the retrofit design changes at the process level, followed by the inclusion of supply chain considerations.

Multi-criteria decision making panel

The MCDM panel consisted of five panel members with diverse backgrounds: two had a corporate pulp and paper industry background, one was an engineering consultant, one was an LCA expert and finally, one was an expert in sustainable development.

The environmental criteria are the impact categories that resulted from the LCA that was carried out (human health, ecosystem quality, climate change and resources). The economic criteria were selected based on their relevance with respect to the design decision problem (Table 3). All criteria are placed at the same decision level in order to increase the panel members' awareness

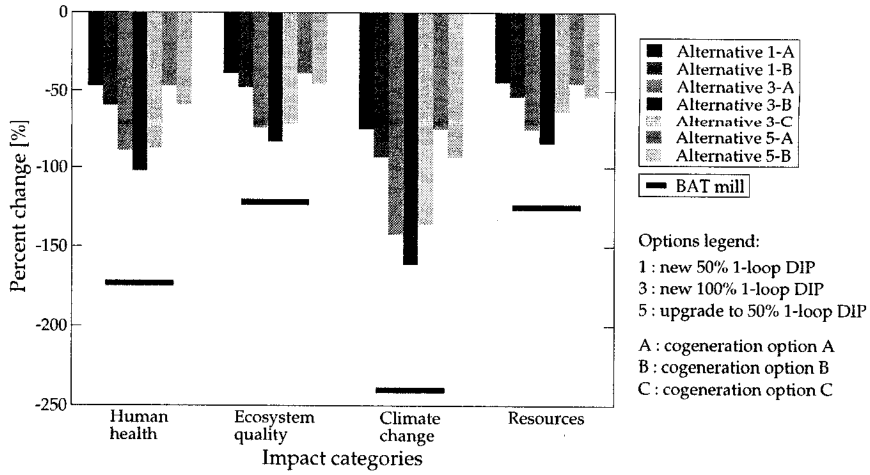

Figure 14: Results of the LCA for the retained design alternatives

Table 3: Economic decision criteria

Criterion	Attribute	Justification for use
Investment	Total capital cost [$]	The pulp and paper industry has limited access to capital
Profitability	Internal Rate of Return [%]	Its target value is usually set by a company
Energy economics	Electrical self-sufficiency [%]	Reflects the mill's independence on external energy sources
Supply chain profit	Annual supply chain profit [$/y]	Market conditions may have an impact on the operations, the supply of raw materials or the demand of newsprint

of the different trade-offs involved in the decision to be made (Fig. 15). At the same time, this avoids comparing aggregated economic and environmental scores, which may lead to an over-weighting of the economic objectives of the decision.

The panel members first established profitability as the most important decision criterion. This was followed by trading off the attributes of the other criteria against IRR (the attribute for profitability) in order to be able to calculate the decision weights (Table 4). The closer the trade-off value is to the IRR target value (20%), the less the panel members are willing to give up on the IRR. The profitability is considered as important as the other decision criteria together and the economic criteria constitute 70% of the total decision weights (Figure 16).

The panel members had trouble trading off the environmental criteria against profitability due to the difficulty of interpreting these criteria and consequently, monetizing them. Furthermore, the panel members' backgrounds and opinions resulted in a large variance in the trade-off attribute values for these criteria. The economic criteria showed a lower difference of opinion between the panel members. One surprising result was that the investment criterion was not given any weight. It was argued that smaller investment projects are often more risky and therefore require a higher IRR.

Next, the overall utilities for the design alternatives were calculated (eq. (3)) using the average

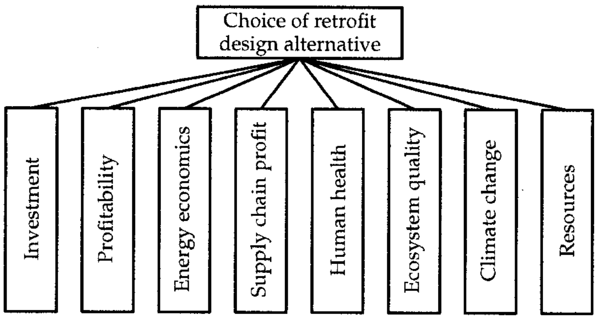

Figure 15: Decision structure for the retrofit design problem

Table 4: Average trade-off attribute values and standard deviation for the criteria vs. profitability (n=5)

Decision criteria	Average trade-off attribute value vs. IRR	Standard deviation
Profitability	n/a	n/a
Investment	20	0
Energy economics	15.6	0.9
Supply chain profit	15.6	1.3
Human health	15.2	3.9
Ecosystem quality	16.4	4.0
Climate change	17.6	5.4
Resources	18.2	2.4

decision weights and the defined utility functions (eq. (4)). Alternative 3-B was slightly more preferable than alternative 3-A (Figure 17). Alternative 3-A outperformed alternative 3-B for profitability, but the latter compensated this by outperforming the former in all other decision criteria. This was mostly due to the higher electrical self-sufficiency of alternative 3-B (Figure 11) and the resulting economic and environmental improvements. The use of criteria whose attributes were calculated with the operations-driven cost and supply chain-level models, besides the profitability criterion, identified alternative 3-B as the most preferred alternative. However, had profitability been used as the sole criterion, as is often done in conventional design decision making, alternative 3-A would have been the most preferred alternative.

For the sensitivity analysis, the average trade-off attribute values and their standard deviations are used as the parameters of the probability distribution functions (Table 4). The outcome of the Monte Carlo analysis shows the same ranking for the alternatives as when using the average weight values only. Furthermore, there is no overlap of the cumulative probability values except for the two most preferred design alternatives, alternatives 3-A and 3-B (Figure 18). This overlap shows that in approximately 90% of the possible outcomes alternative 3-B is preferable to alternative 3-A. Since the overall utilities of these two alternatives based on the average decision weights only were very close (Figure 17), this information would help in making the final decision.

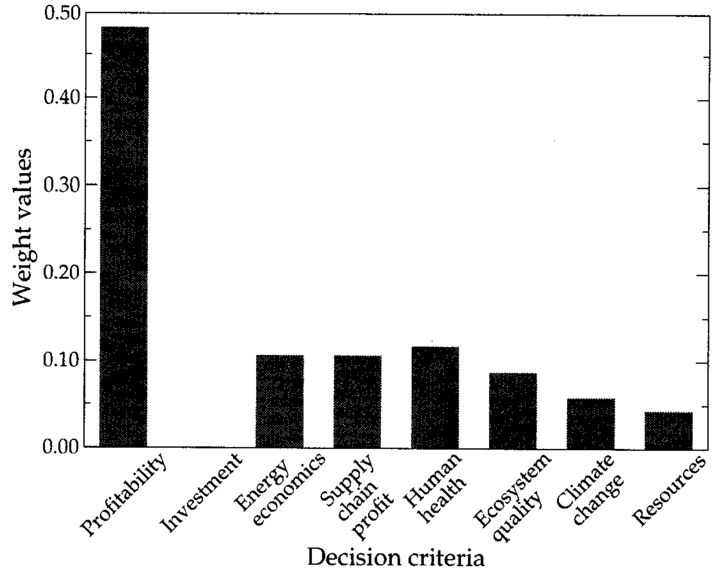

Figure 16: Decision weights based on average trade-off values

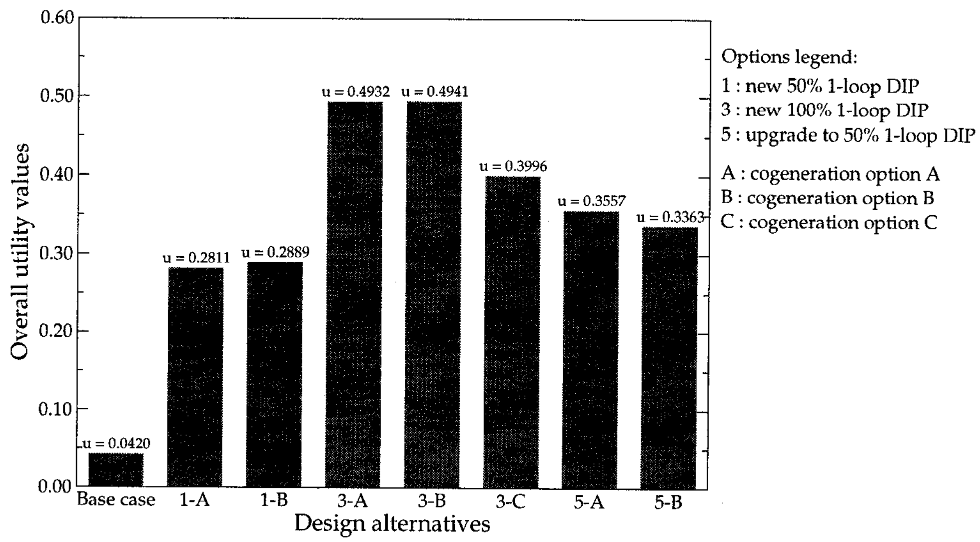

Figure 17: Utility values for the retained design alternatives and the base case mill

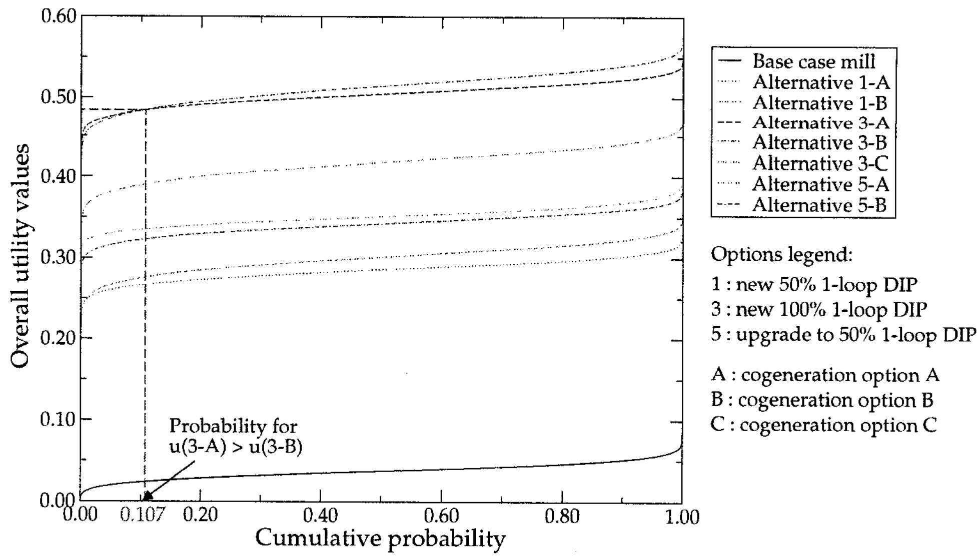

Figure 18: Results of the Monte Carlo simulation for the overall utility of the retained design alternatives

Conclusions

In recent years, Information Management Systems (IMS) have gathered massive amounts of process, cost and environmental data at pulp and paper mills. However, the tools that are currently used focus mostly on *ad hoc* application of these data. On the other hand, process systems engineering (PSE) tools may help to more fully exploit the availability of the data. The goal of this work therefore was to build a methodology that would use these data and PSE tools in order to make better retrofit design decisions. This retrofit design methodology consisted of three steps. First, the existing process and the retrofit design alternatives were characterized at the process level, yielding process and cost information by using mass and energy balances and an operations-driven cost modeling approach. This approach serves as the basis for reconciling process and cost data. In a design context, this means that these data are synchronized, i.e. the cost and process flows along the process correspond with each other. Furthermore, by using Activity-Based Costing-like principles, the resources used are linked to the activities that take place in the defined Process Work Centres. This feature was used in the marginal cost analysis: the activity was steam production in the boilers *PWC* and the fuels used were the resources. By changing steam production levels, the marginal steam cost at different levels was calculated.
Second, the process-level information was used in a supply chain-level analysis in order to determine the economic and environmental impact of the design alternatives at this level. This means that the process level is linked to the supply chain level in a bottom-up manner. As such, this approach first considers the process design, followed by accounting for the supply chain aspects. Due to legal regulations the design alternatives need to be environmentally compliant at the process level. These regulations therefore act as constraints on the feasibility of the alternatives. On the other hand, the supply chain-level analysis elaborates on the trade-offs between environmental and economic decision criteria at this level. Furthermore, more sustainable design alternatives may be identified due to the expansion of the system boundaries by including the supply chain-level analysis. Using the case study, the supply chain-level analysis showed

that the best performing alternative on this level is not necessarily the best performing one at the process level.
Third, a MCDM panel was run in order to determine the most preferred alternative based on process- and supply chain-level criteria. The panel that participated had diverse backgrounds aiding in coming to a more balanced final decision. Furthermore, the decision criteria were placed at the same hierarchical level so as to avoid the trade-off between aggregated economic and environmental scores. The outcomes of the panel indicated that by including other criteria besides profitability, the most preferred alternative may be different than when only using profitability as is usually done in conventional design studies.
This new retrofit design methodology helps to better take advantage of the available process and cost data and extracts information from them that can be used to make better and more sustainable design decisions.

Acknowledgements

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APPENDIX B

COMPLEMENTARY PAPERS

B.1 Survey of data management systems used in the pulp and paper industry

SURVEY OF DATA MANAGEMENT SYSTEMS USED IN THE PULP AND PAPER INDUSTRY

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Abstract

Pulp and paper mills are increasingly implementing process information systems with the goal of better tracking, troubleshooting and optimizing their processes. In the field of process engineering as well as in the field of business process engineering, these information systems are playing an increasingly important role. However, their potential is far from being fully exploited, in large part due to a lack of dedicated resources for applications development at mills. There is also a rapid growth in applications capability being driven by system vendors, expanding the potential for finding value in process data. Some applications in the pulp and paper industry discussed in this paper include: 1. data historians for storing process data and using this data for process trouble-shooting; 2. enterprise asset management systems for streamlining maintenance tasks; 3. manufacturing execution systems for streamlining manufacturing, distribution operations and business processes.

Keywords: *data management, business management, pulp and paper industry*

Introduction

By implementing data management systems, pulp and paper (P&P) mills have dramatically increased the availability of real-time data that can be used to better track, troubleshoot and optimize their procurement, production, distribution and sales processes. Accordingly, these information systems are playing an increasingly important role for pulp and paper facilities (Scharpf, 1999). Real-time data can give mills a competitive advantage by allowing facilities to make rapid and well-informed decisions (Yeager, 2000) and, if integrated at the corporate level, the data can also permit corporation-wide analysis and decision-making. Typically, the overall objective is to use data to simultaneously improve process efficiency by holistic analysis, and improve customer satisfaction by a more efficient management of the value chain within the mill (Lail, 2000). Mills should not restrict their view to the site only (Hagy, 2000) but rather look beyond the boundaries of their own operations and establish inter-organizational systems that facilitate the collaboration between companies in the supply chain.

Application Areas

Process information systems

Process information systems might be considered as data warehouses that consolidate and structure manufacturing data in multiple formats, and make data available for use by mill operations as well as for communication to enterprise resource planning (ERP) systems. Typically, data are stored after being "compressed" by basic data filtering and/or data reconciliation. Important information can then be presented in trend curves or graphic overviews.

In general, a distinction can be made between specific software products configured to address applications particular to the P&P industry, and generic software products that do not offer services and applications directly related to this industry. The advantage of specific products is that their suppliers develop critical applications and services, and enable rapid implementation of value from data management systems. On the other hand, generic products give the costumers the freedom of developing their own applications. P&P mills have generally chosen generic products (OSIsoft, 2002).

Enterprise resource planning (ERP)

Compared to other industry sectors, ERP and enterprise wide management systems are not yet used extensively in the P&P industry but are increasingly likely to be adopted due to globalization (Bottiglieri, 2000; Maxwell, 1999). The newest generation of ERP-products, by focusing on collaborative commerce, enables companies to better coordinate information flows between their suppliers and customers. Indeed, packages increasingly focus on Customer and Supplier Relationship Management (CRM and SRM) and industry portals have been created and customized to transfer information to third parties. Supply chain management plays an important role in developing and cementing relationships with the mill's partners. In this environment, there is significant potential to achieve total cost control and perform real-time value chain optimization. By simulating different scenarios, one is able to find out if an order can be met by applying ATP (Available To Promise), CTP (Capable To Promise) or PTP (Profitable To Promise) criteria. Finally, flexibility is an important asset of an ERP-system in order to be able to adapt to changes in the business environment (Baan, 2002; Honeywell, 2002; JD Edwards; 2002; SAP, 2002).

Enterprise Asset Management (EAM)

The P&P industry is one of the most asset-intensive, and asset maintenance can be a significant component of total production cost (estimated by some to be as high as 30-40 %). This has driven the development of EAM software whose objective is to improve the availability, reliability and utilization of the process assets in order to maximize Return On Assets (ROA). Integration of EAM with an ERP-system provides additional value by reflecting the impact of malfunctioning assets, and adding asset intelligence to the total integrated system, e.g. drawings and manuals. Therfore, preventive planning of maintenance work becomes more efficient and reliable (Avantis, 2002; JD Edwards, 2002; SAP, 2002).

Methodology

In this study, system supply companies were selected on the basis of being active in one or more of the following three applications: EAM, ERP and Process information systems. The following table summarizes the contacted companies by application area. Furthermore, a selection of Canadian P&P mills was contacted, specifically their IT-departments, in order to obtain a perspective of how the mills themselves consider these data management systems.

Table 1: List of participating companies

EAM	ERP	Process informations systems
Avantis	Baan	Kvaerner MOPS
IFS	Honeywell	Metso
JD Edwards	JD Edwards	OSIsoft
SAP	SAP	

Results & Analysis

Four basic product development goals were identified by the software suppliers participating in the survey:

- **Data management**: collection, storage and presentation of data to ensure data accessibility.
- **Syatem Integration**: for most of the suppliers, full integration is a necessity.
- **Maximizing ROA**: providing software and services to streamline maintenance, inventory and procurement activities.
- **Quality management**: process management is tightly linked to quality management by e.g. production loss analysis.

Clearly the focus is on IT-issues (data management and integration), and suppliers have considered less the effectiveness of the operation (maximizing ROA) and responsiveness towards customers (quality management).

The reasons why pulp and paper mills implement data management systems are related to the following points:

- **Effectiveness**: Improved profitability is given a high emphasis in mills, and implemented systems focus on operations management, reliability focused maintenance and process analysis.
- **Responsiveness**: High sevice levels to customers, meeting short lead-times, handling variability and quality management.
- **Data Access for Decision-Making**: Transparency and access to data throughout the facility are important.

The surveyed P&P mills use a wide spectrum of applications by Honeywell, i2, AspenTech, SAP, Indus, PeopleSoft, Kvaerner MOPS, Majiq, MRO, ABB, OsiSoft, Foxboro and Oracle or sometimes, systems developed in-house. P&P mills typically have process information systems (mainly OSIsoft) for process data and EAM systems. None of the mills surveyed had an ERP system. Figure 1 summarizes the factors that the surveyed mills considered for implementating new data management systems.

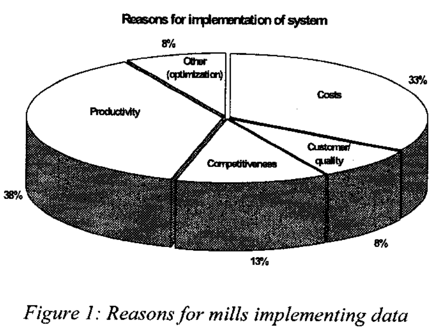

Figure 1: Reasons for mills implementing data management systems

Benefits & advantages of the implemented systems

After implementation, it is interesting to note that mills indicate that the primary value of the data management systems was simply from getting process information to the right people in a timely fashion. Overall, mills indicated that they are pleased with the systems in place and most of them would choose the same software products again.

More specifically, the principle benefits of the systems were described as follows:

1. **Effectiveness**
   - Reduced work-in-progress (WIP) inventory;
   - Process analysis and optimization;
   - Process troubleshooting;
   - Better maintenance management.
2. **Responsiveness**
   - Accurate ATP and CTP;
   - Quality monitoring.
3. **Information Technology (IT)**
   - Visibility of the mill operation in real-time to all departments within and outside the mill.

The noted benefits are mostly in the effectiveness of their operation as summarized in *Figure 2.*

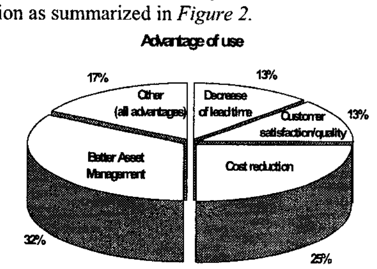

Figure 2: Advantage of the use of data management software

Criteria of selection and comparison

The following are the main criteria used by mills to select a system:

- **Cost of implementation and cost of ownership**: although this is not the driving force behind selecting a system, it is an important criteria. Costs items include purchasing agreements, service contracts with system vendors, and development costs.
- **Experience in the P&P industry**: selection of a product that has already been adapted to their needs.
- **Integration with existing systems**: ease of integration with systems already in place at the mill.
- **Availability of strong local support**: remaining up-to-date with the latest technology developments.
- **Ease of use**: the user-friendliness of the system.

Mills do not see big differences between the systems that are available on the market because few functional features distinguish them. In contrast, the software suppliers try to differentiate themselves based on many criteria. Typically they focus on the items identified above for system selection and in particular, the ability to provide value-added services that help organizations maximize the use of the software tool.

The most important similarity between the mill criteria of choosing a system and the differentiators between software suppliers is the amount of experience in the P&P industry. Still, there are only a few suppliers who focus on P&P applications - Kvaerner MOPS and Metso DNA. In contrast, other suppliers' strategy (e.g. JD Edwards and Osisoft) is to develop generic software packages that can be applied in any industry. Some suppliers focus more on IT-related issues than on the needs of P&P mills.

Modes of Implementation

Generally, systems have been implemented mainly at the mill, by both corporate and the mill, or primarily by corporate. The systems have been implemented and developed mainly internally and with the help of consultants. The mills have software maintenance agreements with the software vendors that provide the latest software releases, product support and reduced training costs. The systems are managed by the IT-department at the mills, while the applications are managed by the users.

Only in a few cases mills have linked their systems or part of their systems to customers. The main reason for this is that the mill is concerned over who is accessing the data and therefore, fear of competition and a lack of trust of the partners. Nevertheless, some suppliers have linked to the mill systems for automatic monitoring of levels of the suppliers' products at the mill. However, new communication technology like the .NET-protocol will enable better information exchange with sufficient security.

Improvement of systems

Mills identifies that they seek improvement in the following fields:

- Better integration of disparate data sources;
- Flexibility;
- User training;
- Higher resolution of data collection;
- System management and development;
- User-friendliness;
- Reference to non-time based data.

As can be seen, these fields focus on issues related to information technology. The IT-department manages the systems and were contacted fpr this survey.

In the future the mills would like to see improved ease of implementation, better integration, higher flexibility and greater input of real-time information. Furthermore, since the P&P industry is asset intensive, the mills want more advanced solutions for life cycle management of products and assets. As shown in *Figure 3*, there is also a great interest in solutions for advanced planning and scheduling and collaborative commerce.

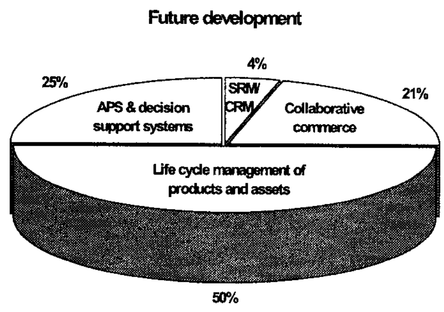

Figure 3: Interests of mills in future development

Certain of these solutions are already available on the market but the level of technology at the mills is less advanced than the state-of-the-art offered by suppliers. So far, software are generally horizontally integrated at the mills. With vertical integration of software, the true value of data can be better explored, e.g. the engineering department and the accounting department will use the same relational database to find information.

Data warehouses, where both continuous and discrete data can be stored and related, are powerful tools to reach this vertical integration and for example enable advanced planning and scheduling and improved decision making. In the short term, mills should be ready to embrace these applications. Furthermore, in the longer term, collaborative commerce will become more and more important because of the globalization of the market and the focus of competition between supply chains instead of independent companies.

The following are the main development areas for systems that the suppiers identified:

- transformation of data into meaningful information;
- methodologies to obtain a representative selection from large data quantities, sorting out erroneous data and handling missing data;
- Application of technologies including Microsoft.NET strategies and Java-applications.

The possibilities that exist for using data to add value to industries are limitless but the critical question is whether the developed application makes sense business-wise. Should the developed application "drive" basic business decisions over other strategies. The experience and acquired knowledge of pulp and paper processes and business models must be carefully combined to implement applications.

Conclusions

A detailed survey was conducted in order to get a clear understanding of the software products available in the field of manufacturing and data management, and how they are currently - or potentially - implemented in the P&P industry. Software suppliers were selected on the basis of being active in the field of Enterprise Asset Management, Enterprise Ressource Planning and Process Information System. Several Canadian P&P mills participated in the survey in order to get a clear picture of the practical use of the software products.

Altough the interpretation of data from data management systems has not been extensive, it is now growing steadily. Nowadays, process information systems and enterprise asset management are the two most used applications while ERP is still rarely used at the mill level. Interestingly the most important criterion identified by the surveyed mills for choosing a system is the supplier's experience in the P&P industry, whereas only few of them truly focus on vertical industry applications. Data interpretation and so-called vertical integration are the most important issues that need to be addressed for applications such as improved decision making and advanced planning and scheduling.

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B.2 Survey indicates mills' need to exploit IT systems with new business model

A survey shows how North American mills use information systems and how a business model supported by such systems should integrate cost and process data

Survey Indicates Mills' Need to Exploit IT Systems with New Business Model

By M. JANSSEN, M. LAFLAMME-MAYER, M-H. ZEINOU, AND. P.R. STUART

In recent years, pulp and paper mills in North America have integrated their information management systems (IMS) to a significant extent, creating millwide data and information repositories to support multiple applications and provide information for a variety of users, such as managers, engineers, and operators. Mills have recognized the benefits of IMS, such as improved data accessibility and opportunities to use real-time data for addressing process issues.

However, the potential value of IMS has not been fully exploited, especially the application of data in process analysis tools for making better operating and design decisions. For example, the potential for using IMS for business process analysis and supply chain management is generally undervalued, or in some cases, still unrecognized as an important opportunity at the mill level.

The main barrier to enhancing value from IMS is the lack of available resources. This article offers an approach to business modeling that uses process, accounting, and environmental data. This facility business model could provide cost and process data for subsequent model development and better decision making.

The results presented here are based on a survey of Canadian (69%) and U.S.-based (31%0 pulp and paper mills. Respondents included information technology (IT) managers (56%), process managers (31%), and mill managers (13%). The conclusions that were drawn are consistent with a previous survey about the use of data management systems (DMS) in the pulp and paper industry.[1] A DMS is a software system that facilitates the creation and maintenance of databases for data acquisition and storage, as well as the execution of computer programs using the databases. It is part of an IMS.

The goal of the survey reported in this article was to address the following issues:

- Justification for and methods of implementing IMS
- Benefits of millwide system integration
- Prerequisites and barriers to millwide system integration
- Future plans for IMS

Current Uses for Information Management Systems

Survey respondents reported the use of a myriad of software packages. The most frequently mentioned ones were SAP (33%) and JD Edwards (17%). Other packages included SSA Infinium, Oracle Financials, Epicor eBackOffice, Majiq Elixir, and MRO Maximo.

Examples of IMS applications included the following:

- *Product tracking back to the wet end.* This is an effective tool that offers flexibility in production decision making and provides important business data.
- *Maintenance.* The maintenance system can be used for costing, including labor and purchasing (which can be automated).
- *Online cost tracking.* Cost calculations can be based on online data, e.g. raw material, allowing for calculations based on grade and customer.
- *Lost production system.* This system gives monthly statistics (e.g. equipment availability) for areas where most losses occur. The system can help target areas where maintenance or capital spending is needed.

A majority of the survey respondents stated that IMS overall enhances the sharing of mill information (73%). Some mills use an intranet for this purpose (30%). In most mills, there is a link to the corporate level for cost reporting. Although 63% of the respondents noticed a better response to identified problems with IMS, this is difficult to assess because mills do not keep appropriate metrics. According to the respondents, the

TABLE 1.

Issues used by survey respondents for justifying an information management system purchase

Justification for Purchase of IMS	%
IT-related issues	
Ability to store information more efficiently	90
Architecture for the millwide integration of applications	67
Management of distribution and collection of information	60
Connection of legacy systems with new systems	47
Process-related issues	
Acquisition of data coming from the production process	80
Correlation of information coming from different systems	78
Gathering of data to solve problems	78
Integration of mill processes and supporting activities	73
Repository system for storing obtained knowledge	60
Millwide decision system for operational support	60
Better response time related to incoming orders	60

TABLE 2.

Ranking of issues for justifying an information management system purchase by IT and non-IT survey respondents (1 = highest rank, 6 = lowest rank)

Justification for Purchase of IMS	Rank	
IT-related issues	IT	Non-IT
Ability to store information more efficiently	1	1
Architecture for the millwide integration of applications	2	4
Management of distribution and collection of information	3	2
Connection of legacy systems with new systems	4	2
Process-related issues		
Acquisition of data coming from the production process	3	1
Correlation of information coming from different systems	1	6
Gathering of data to solve problems	1	3
Integration of mill processes and supporting activities	3	3
Repository system for storing knowledge	7	1
Millwide decision system for operational support	6	3
Better response time related to incoming orders	5	6

challenges of data sharing are related to system management (from a technical point of view) and ensuring that personnel are trained and understand the systems.

IMS can help improve cost accounting by tracking costs in a more detailed manner, and results are delivered in a more timely fashion. Of the respondents, 20% stated that they have an online cost-tracking system allowing them to track costs in real time, whereas most mills rely on manual data entry and spreadsheets for coupling process and business data. The impact of IMS for evaluating and controlling the variability of costs such as electricity use, labor, and overhead costs is considered important, with 85% of the mills using IMS for this. Some mills (33%) consider supply-chain activities (of some definition) in their cost systems.

Forty-two percent of respondents considered the data management system as the heart of their IMS. The most frequently used data management system is the PI-system from Osisoft (42%). Other DMS systems that were mentioned include MOPS, Aspentech IP.21, and Honeywell PHD. In some mills (17%), there were no DMS implemented. Also, the mainte-

Process Integration Techniques Offer Insight into Paper Processes

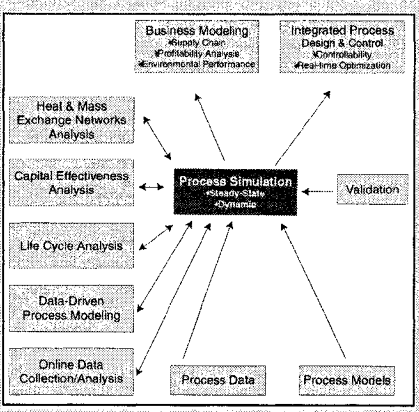
Mills consist of complex interconnections between process units, whose overall operation should be optimized for objectives related to economy, operability, and environment. Process integration (PI) is the term used for the application of systems-oriented approaches to industrial process plant design.

In the early 1980s, PI's initial focus was to reduce energy consumption, but the methods have since been enhanced to address more industrially realistic objectives such as total annualized cost, mill operability, and mill flexibility. More recently, environment and sustainability have become an important focus of PI.

The pulp and paper industry is increasingly characterized by the impact of the "new economy" driven by return on capital employed (ROCE). So, the application of PI methodologies using real-time process and accounting data is increasingly critical for the competitive position of mills. PI can be adapted to the specifics of pulp and paper processes to achieve goals such as reduction of effluent and other environmental impacts, energy efficiency and energy cost reduction, improvement in material yields through optimal use of raw materials, and de-bottlenecking to increase production flexibility or capacity.

PI methodologies have been applied to address problems facing the pulp and paper industry as the nearby diagram shows. For example, wavelet transform techniques were applied for data processing with the objective of removing signal noise and abnormalities in real-time data and for the detection of process steady state. These techniques are combined with data reconciliation techniques to develop high-quality databases for validated steady state millwide process conditions.

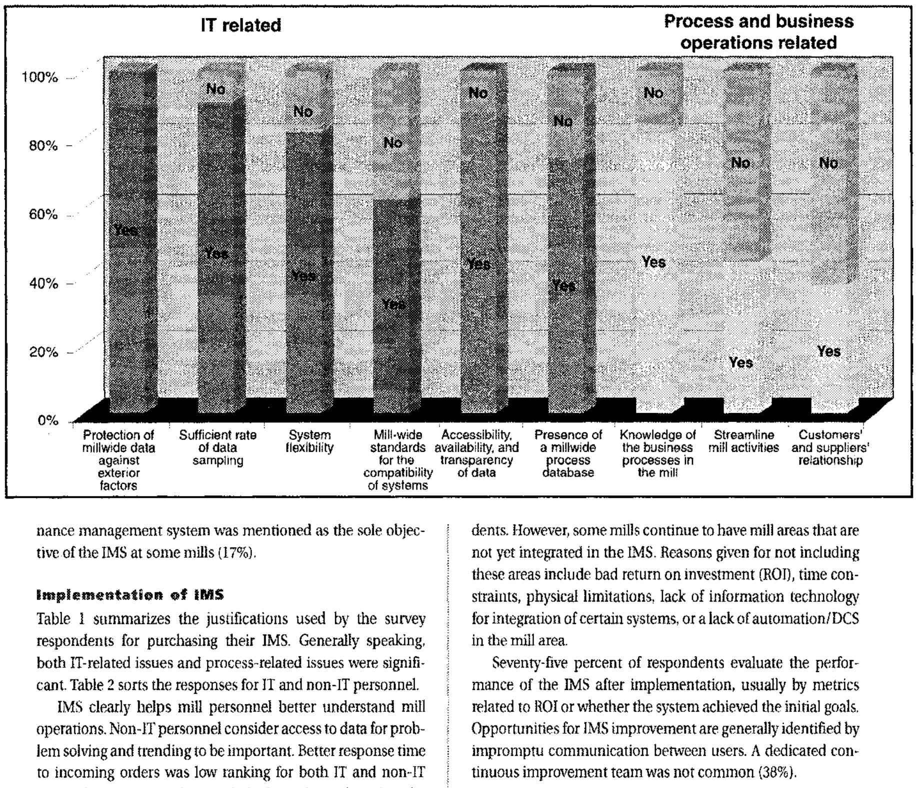
In other work, multivariate analysis (MVA) is used to explore the impact



of data quality, differences in data characteristics, and the effect of parameter variability on MVA outcomes in the context of estimating pulp and newsprint quality. A strategy for "life cycle thinking" has been developed, and the potential for applying LCA techniques in environmental impact assessments and environmental management system metrics has been examined.

FIGURE 1.

Prerequisites for system integration as determined by survey participants



nance management system was mentioned as the sole objective of the IMS at some mills (17%).

Implementation of IMS

Table 1 summarizes the justifications used by the survey respondents for purchasing their IMS. Generally speaking, both IT-related issues and process-related issues were significant. Table 2 sorts the responses for IT and non-IT personnel.

IMS clearly helps mill personnel better understand mill operations. Non-IT personnel consider access to data for problem solving and trending to be important. Better response time to incoming orders was low ranking for both IT and non-IT respondents. One might conclude from these data that the expectations of IMS were not high and the power and capabilities of IMS are underrated.

Respondents were questioned about IMS for business process analysis. According to all respondents, business process analysis is considered critical. Seventy percent of respondents identified that with the implementation of IMS, business processes were analyzed and changed in order to make them more efficient. However, only 20% of mills said that a business process analysis was repeated following IMS implementation.

IMS has been implemented millwide for 80% of respondents. However, some mills continue to have mill areas that are not yet integrated in the IMS. Reasons given for not including these areas include bad return on investment (ROI), time constraints, physical limitations, lack of information technology for integration of certain systems, or a lack of automation/DCS in the mill area.

Seventy-five percent of respondents evaluate the performance of the IMS after implementation, usually by metrics related to ROI or whether the system achieved the initial goals. Opportunities for IMS improvement are generally identified by impromptu communication between users. A dedicated continuous improvement team was not common (38%).

Millwide System Integration

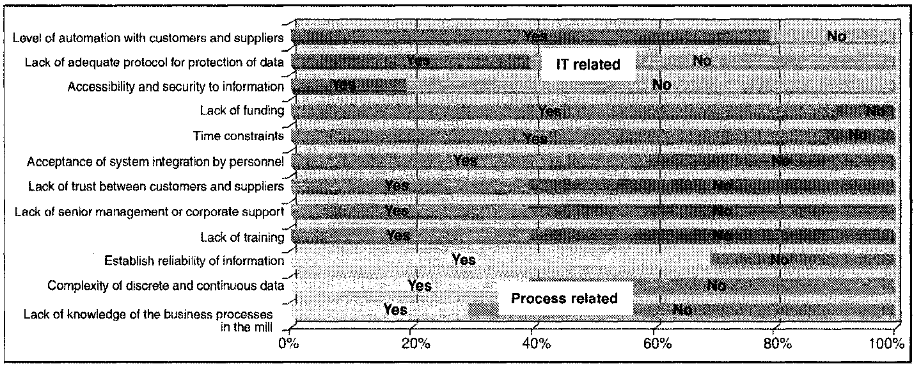
The survey respondents were asked about prerequisites for system integration. Figure 1 shows that IT-related criteria are considered the more important prerequisites. According to the respondents, the mill business processes need to be well understood in order to achieve integration. This is particularly recognized by non-IT personnel.

Overall, there is a low recognition of the importance of the supply chain, and IT-personnel were more apt to recognize the value of the supply chain than non-IT personnel.

Figure 2 summarizes barriers for millwide systems integra-

FIGURE 2.

Barriers for reaching system integration



tion. Perhaps not surprisingly, lack of funding and time constraints were the biggest barriers. Respondents also saw acceptance by personnel as a barrier for reaching system integration (60%), indicating that some mill personnel were reticent to give up information ownership. Lack of business process knowledge was not considered a barrier for most of the responding mills.

Respondents assessed a list of benefits and impacts, categorized as either IT related or process related, and Figure 3 summarizes their responses. System integration has a significant positive effect on IT-related issues in particular. Clearly, the implementation and integration of IMS was considered successful.

Decision making was also enhanced by the implementation of IMS. However, this does not necessarily imply that advanced data analysis or decision-making tools were used to achieve this. The increase in the availability of online data enhanced the ad hoc capability of problem solving.

Value of IMS for Mill Activities

Several questions were formulated to determine how the IMS adds value to the operation of a mill (Table 3), as well as which

FIGURE 3.

Impacts and benefits of reaching system integration

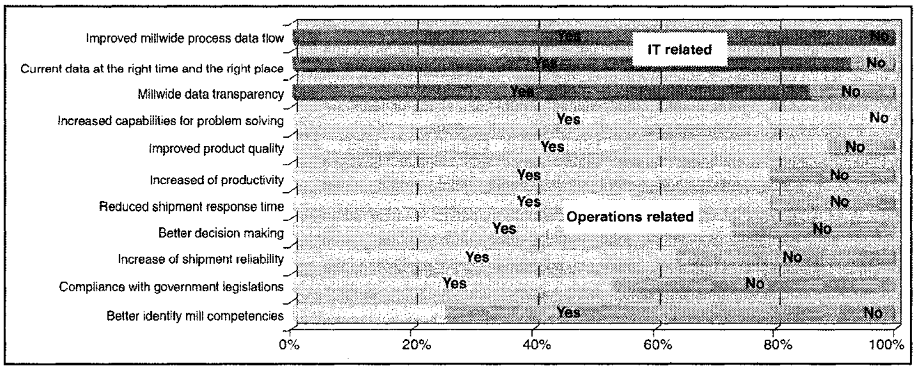
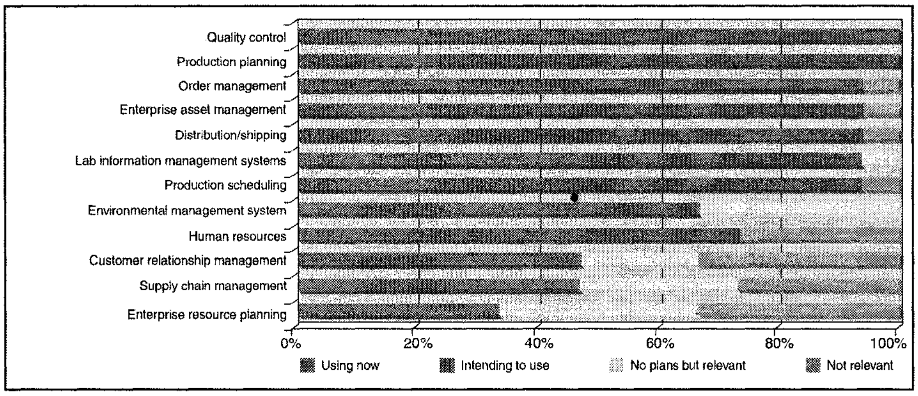


FIGURE 4.

Survey participants indicated how software was used in their mills.



applications are used (Figure 4). Most mills report a major improvement in operations due to IMS use, but supply chain activities get little attention. Business issues are valued higher by non-IT personnel when comparing the responses of the two groups (data not shown). Although it appears that most operations-related applications have been addressed to some extent, survey participants acknowledged that a significant amount of work remains. A significant proportion of the respondents did not plan on implementing ERP, SCM, and CRM in the near future.

The respondents were questioned about the acceptance and use of IMS by personnel. Most survey participants (88%) stated that employee acceptance of IMS continues to be a challenge, citing resistance to change as the principal reason. Users may fear that the implementation of a new system will lead to the loss of their customized old system. Also, operators may see IMS as a management tool for upper management more than as a process tool that helps them directly. Training and change management are clearly of great importance.

IMS applications have increased the knowledge and skills of mill personnel, according to 75% of the respondents. Most people are comfortable with using the system data for problem solving. Critical prerequisites for the success of IMS applications include the ability to use the tools, an understanding of the processes and business processes, and a willingness to share data.

Future Uses of IMS

When asked about their mills' vision for IMS over the next three years, respondents replied that IMS would continue to be enhanced by further implementation of systems, tighter integration, upgrades, and increased accessibility to information. Sixty-two percent of the respondents intend to upgrade their existing systems, while 38% have no specific plans. Moreover, many mills (62%) do not intend to initiate change in the supply-chain management.

Creating a Mill Business Model with IMS Data

It is clear that the implementation of IMS at mills has opened up opportunities for innovation by making available massive amounts of data, but survey results indicated that the potential for using IMS data is not yet fully exploited.

Until now, data have been used for troubleshooting, generally through impromptu analysis of real-time data to enhance process understanding. Cost data are still not highly integrated

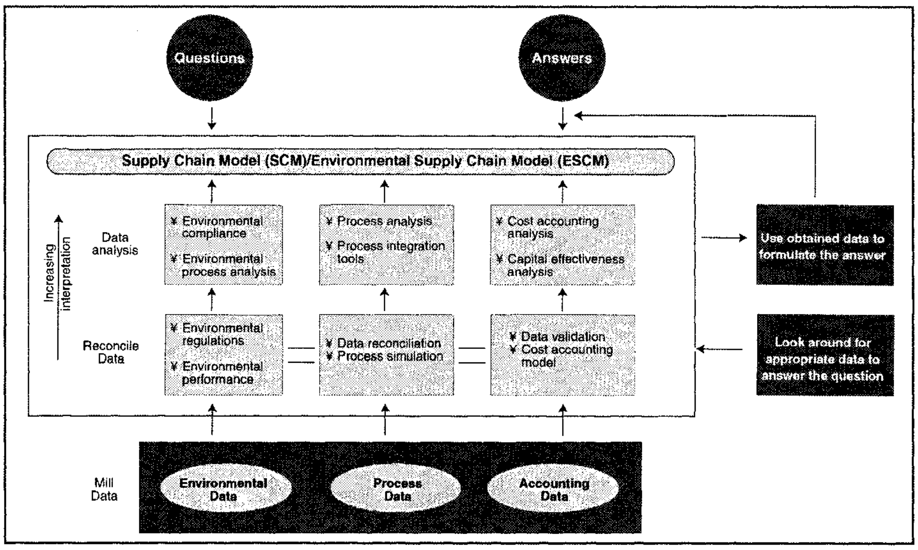
TABLE 3.

Average rank of dependence of mill activities on IMS as ranked by survey participants (1=highest rank, 8 = lowest rank)

Mill Activities	Average rank
Operations	1.90
Financials	3.89
Human Resources & Payrolls	4.11
Logistics	4.15
Quality Management	4.40
Environment	4.50
Procurement	5.83
Customer relationship Management	6.81

FIGURE 5.

Schematic of proposed business model that incorporates data from a range of areas within the mill



with process data in most mills. It is clear that a better understanding of the business processes could potentially enhance the value of IMS significantly.

By carefully combining process and accounting data, their correlation will become more evident. The environmental impact of the operations and the products along their life cycle can also be explicitly considered, as can the supply-chain model.

Figure 5 proposes a mill business model that incorporates different types of data and expertise into a single model that might be effectively used with process integration tools to achieve both process design and operations improvements (see sidebar).

Figure 5 shows environmental, process, and accounting data from the IMS being reconciled and then incorporated into models reflecting historical mill operation. Data are attributed to different mill areas. The model could reflect changes to mill design or operation of the mill and could estimate revised process, environmental, and cost efficiencies.

This business model is facility oriented and considers the operation of one mill, including the life cycle of its products. The proposed business model would be structured such that it can be expanded to a multi-site, enterprisewide model. P&P

1. Janssen, M., Laflamme-Mayer, M., and Stuart, P., 2003, "Survey of Data Management Systems Used in the Pulp and Paper Industry," *Proceedings, FOCAPO 2003: Foundation of Computer Aided Process Operations*, Coral Springs, Fla., pp. 551-554.

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B.3 Business model framework for using real-time process data for design decision making

Business Model Framework for Using Real-Time Process Data for Design Decision Making

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Abstract

In recent years real-time data management systems have become commonplace at pulp and paper mills, and mills seek to use this important resource for improved operation of production facilities as well as for business decision-making. This paper presents a comprehensive and holistic approach to business modeling in which real-time process data, cost data, and environmental data are used in a "bottom-up" manner to exploit their potential for process decision-making. The paper describes a hypothetical case study in which the business model concept is illustrated by application to a process design problem at an integrated newsprint mill.

1. Background

1.1 Real-time data usage at pulp and paper mills

In recent years, real-time process data have become widely-available at pulp and paper mills through the implementation of mill-wide data management systems that acquire, store, and manage data. In addition to data management systems, mills are also implementing systems that capture business transactions, track product quality, or help manage human resources. Together, these systems help pulp and paper mills to better understand their operations and tackle critical problems – both tactical and strategic. Process analysis can be executed taking into account the whole mill, instead of only a single unit or a small system. Process performance can be improved using a combination of process efficiency metrics, cost metrics and environmental metrics.

Information management systems (IMS) have been implemented since the late 1970s and have been expanding over time as existing or new subsystems or applications were integrated. An IMS is a mill-wide data and information repository, which supports multiple applications that provide the information required by different mill stakeholders such as managers, engineers, and operators. Distributed control systems (DCS) and maintenance systems were the first to be implemented mill-wide. However, these systems were capable of gathering, but not storing large quantities of data. In recent years, packages such as PI by Osisoft Inc. [15] or MOPS by MOPS Systems [26] (which focus on process data), and SAP [23] or PeopleSoft [17] (which focus on business data), have been implemented in the industry, either mill-wide or company-wide.

Several examples of IMS applications in the pulp and paper industry have been reported in the literature (Table 1).Table 1 illustrates the wide range of IMS applications. However there remain many more opportunities to be exploited. The examples in Table 1 can be characterized by a "top-down" or reactive approach to problem solving. However, the opportunity to extract process knowledge from the data is not fully exploited. For attaining full exploitation, pulp and paper mills and companies can alternatively use a "bottom-up" approach, which incorporates knowledge from the interpretation of available data in real-time for mathematical modeling of processes in the mill. Process integration techniques generally use this "bottom-up" approach. For instance, process data can be used in many mathematical optimization applications to improve process decision-making.

1.2 Current pulp and paper industry priorities

The pulp and paper industry currently faces numerous and significant challenges. For example Leaver & Scott [14] summarize some key issues related to industry image on the stock markets, capital intensive infrastructure, uncertainty in the supply and pricing of

Table 1: Applications of IMS in the pulp and paper industry

Mills	Application
Alabama River Pulp Co. Inc. (Perdue Hill, AL) [28]	Processes are better synchronized, performance is tracked, and process problems are better characterized
Georgia Pacific (Plattsburgh, NY) [16]	Systems are used for maintenance diagnosis, process troubleshooting, and the tracking of grade specifications
Abitibi-Consolidated Inc. (Jonquière, QC) [18]	Instrument and control loop integrity are verified, and routine maintenance tasks are streamlined
Abitibi-Consolidated Inc. (several mills, ON) [20]	Power consumption is monitored and planned to decrease cost in a deregulated power market
Madison Paper Industries (Madison, ME) [24]	Business processes are supported and the financial performance is tracked in real time

energy and raw materials, as well as the need for innovation in equipment and machinery. Solutions addressing these challenges would provide opportunity for industry rejuvenation, or at least competitive advantage. The availability of IMS data has given the pulp and paper industry an extra resource for tackling these very problems. Ritala [19] describes that process efficiencies, and especially capital and supply chain efficiencies are key to the pulp and paper industry. Ritala highlights key data-driven opportunities to achieve these goals including for example modeling and dynamic simulation as tools for studying process variability to reduce operational problems such as paper machine breaks. Advanced optimization based on real-time data can be used to improve production scheduling, and advanced process control strategies such as model predictive control can be used for automatic grade changes.

These changes are manifested in the corporate goals of leading pulp and paper companies. For example fine and specialty paper producer Domtar has announced five objectives for improving their performance as a company [4]. These objectives are to enhance customer loyalty, to double the size of the company, to improve productivity, to continue good citizenship, and to maintain the financial return edge. Information and knowledge can be extracted from the available data in order to reach these goals, for example:

- Enhancing customer loyalty requires a more flexible and a higher-performing delivery system, which can be obtained by the implementation of supply chain management (SCM).
- Doubling the size of the company is generally met by the acquisition of other companies, which in turn is possible by strong share prices. The stock market today insists on a strong Return on Capital Employed (ROCE) performance metric from pulp and paper sector companies – achieved through incremental production increases and operating price decreases from existing facilities which can be identified through a variety of process integration techniques. As well, tools such as life cycle assessment (LCA) can be used to illustrate excellence in environmental and energy performance from the product perspective and enhance share price from this perspective.
- For improving productivity, one needs to know the key impacts on the net profitability and performance of the mill processes, and be able to quantify these impacts through cost management and holistic process analysis. This can be facilitated by a holistic business model such as that described in this paper, and by analyzing product mixes using sophisticated applications of process integration based on supply chain modeling.
- Good citizenship can be achieved by combining environmental and social risk management with solid financial performance.
- In order to attract quality investors, Domtar seeks to maintain a financial return edge. Good financial returns can be measured in many ways, but are achieved by being perceived as providing a quality product for a reasonable price while having competitive production costs.

All of these goals can thus be addressed using process integration tools, and require multi-criteria decision-making based on a consistent set of data.

1.3 Surveys on the use of IMS

In 2002, an initial survey about the use of data management systems (DMS) in the pulp and paper industry was conducted amongst Canadian pulp and paper mills and vendors of data/information software [8]. A data management system is comprised of software that facilitates the creation and maintenance of databases for data acquisition and storage. Data management systems are one component of IMS. In 2003, another survey of American and Canadian mills was executed about the use of IMS in the pulp and paper industry [9]. These surveys confirm that huge

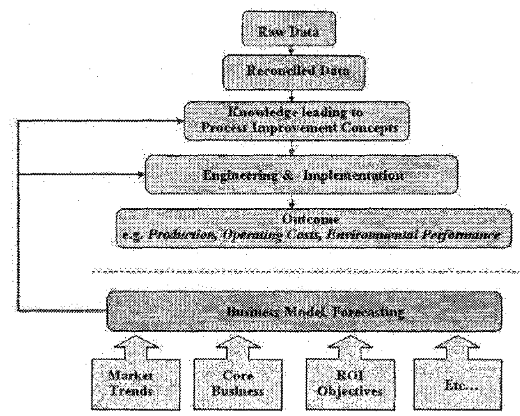

Figure 1: Classical engineering design process employed in the pulp and paper industry

datasets have been stored at pulp and paper mills and data are now widely available to mill personnel, but the true value of the data has yet to be fully exploited. Reasons for this include a lack of time and money to invest in this goal, and apprehension about how to systematically develop the correct systems and obtain a high return on investment. Despite these obstacles, the interpretation of data is still considered to be critical to the competitive position of mills. Furthermore, the surveys showed that until now, the benefits from using data are mostly related to the characterization and *ad hoc* analysis of operations. A practice that is not yet common is the coupling of process and business data, through means such as real-time costing systems that make use of process data coming from the data management system.

This paper proposes a business model which is a holistic framework that can be used for process, business, and environmental decision-making.

2. Novel business model concept

2.1 Classical process design in the pulp and paper industry

The traditional design process in the pulp and paper industry is illustrated in Figure 1, and has involved many engineers at the mill and corporation. Today, the engineering capacity at both these levels has been drastically reduced. However in many ways, the engineering processes have not been adjusted to reflect these cut-backs.

Capital spending is based on increasingly sophisticated analyses of market trends, established core business areas, ROI objectives for shareholders, etc. These objectives and insights are relayed to mill managers and engineers, who in turn identify opportunities for design improvement consistent with company priorities. Many of these can potentially be systematically incorporated into the business model concept proposed here.

Process simulation results are combined with financial and accounting information in an *ad hoc* fashion in the classical design process, in order to identify the most economically viable design options. Cost data have not been tightly integrated with process data in most mills, and changes in process design or operations are perhaps not accurately reflected in mill-wide costs. By combining the production process and the accounting system into one model such as proposed here, their mill-wide correlation will be more precisely reflected.

Data compiled in the business model described in this paper combined with process integration tools for process analysis assist in the goal of *despecialization*, where one engineer is better able to understand data issues (e.g., cost, process and environmental) through to the outcomes (e.g., product quality, capital costs, operating cost changes) from process improvement projects.

2.2 Overview of business model concept

The business model proposed here utilizes cost, process and environmental data in conjunction with process design and operations analysis tools (see Figure 2). The analysis of processes for improvements in operations and design are executed using various process integration tools.

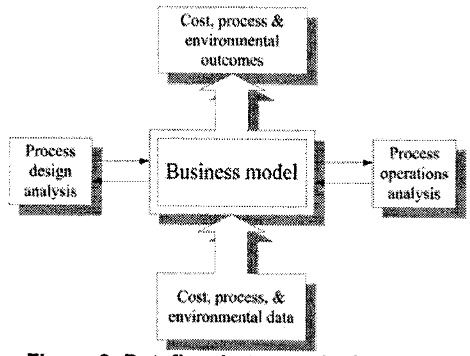

Figure 2: Dataflow between the business model and process design and operations analysis

Process integration (or process systems engineering) is a holistic approach for process design and operations, which emphasizes the unity of the process. It uses mathematical tools in conjunction with process expertise in order to extract information from the real-time data that are collected from different data sources. Real-time data are thus transformed into knowledge (through fundamental and empirical models), which can then be used for decision-making. The business model is facility-oriented and considers the operation of one mill and its products.

The center line in Figure 2 represents the transformation of raw real-time data into mill-wide knowledge via the business model. An expansion of the center line of Figure 2 is presented in Figure 3. The proposed business model concept can be divided in the following parts:

1. Data treatment activities which process and reconcile real-time process data, accounting data, and environmental data that are used in the business model.
2. Data input into models in which the process, economic and environmental data are utilized. Process data is also used in the accounting and environmental models. These models should ideally characterize the cost, process and environmental performance of individual mill areas.
3. Data input into product chain models in which the mill product(s) can be followed along the life cycle, and to which the businesses constituting the supply chain are included in the model.

It is possible to expand the model to a multi-site, company-wide model and to consider the overall supply chain in which the mill or company takes part.

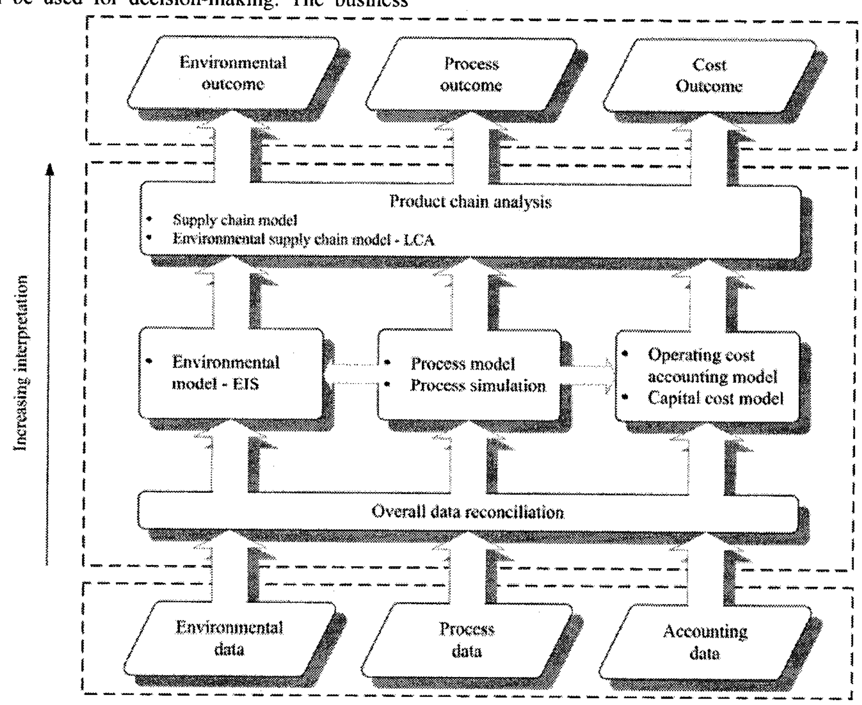

Figure 3: Schematic of the flow and processing of data within the proposed business model

The business model is highly data-intensive. With the advent of IMS, this challenge has become less restrictive. However, data quality remains an issue. Also, since the business model uses historical data for making decisions for the future, uncertainty in the data plays an important role that needs to be taken into account for decision-making.

2.3 Data treatment considerations

Real-time process data must be mathematically processed (i.e., treated to eliminate noise and abnormalities). Measurement noise has frequencies much higher than normal process variations, whereas abnormalities are defined as spikes in the measurement with a supra-normal value and a short duration. A wavelet-based multi-scale data processing approach has been used to process pulp and paper mill data [11]. Next, steady state detection can be performed for the processed data set in order to identify near steady state operation. The treated steady-state process data can then be used in data reconciliation (also shown in [11]), so that gross errors are detected and the quality of the process data is increased. When these data processing and reconciliation steps have been executed many times over a long time period, a probability of occurrence can be established for each process parameter at each mill operating regime.

Next, the relationships between the process data and the accounting and environmental data can be modeled (see Figure 4). Using these relationships, an overall data reconciliation model is built and the reconciliation is performed in order to generate a single coherent and reliable data set. A feedback loop from the overall data reconciliation can be used for an iteration of the process data reconciliation and a re-validation of the accounting and environmental data until the desired coherency is attained, and can be used to update relationships based on on-line data acquisition and treatment. The coherent data set is used in the process, accounting, and environmental models of the business model.

2.4 Process modeling aspects of the business model

Process modeling can be performed based on first principles models, and/or based on data-driven empirical models. First principles modeling uses the energy and mass balances derived from the process under study [13]. Data-driven modeling uses available data in conjunction with inductive mathematical techniques such as neural network modeling or multivariate analysis (MVA) to generate empirical models [6]. Empirical modeling is often used when complex phenomena must be considered which do not lend themselves well to fundamental modeling. Often, in pulp and paper process modeling, these two approaches can be combined to form hybrid models.

2.5 Activity Based Costing (ABC) accounting aspects of the business model

Activity Based Costing (ABC) is a cost accounting method that first accumulates costs for each of the activities of an organization, and then assigns the costs of these activities to the products, services, or other cost objects that caused that activity [7]. The benefits of using ABC and ABC-like accounting are numerous. Perhaps the most important is the ability to better allocate overheads when compared to traditional volume-based costing methods [5].

ABC differs from traditional volume-based costing systems in that [5]:

- Cost objects consume activities and these activities consume resources,
- ABC uses activity and resource drivers to trace costs to objects in a causal manner.

The ABC costing method is a model that is process-oriented and is therefore a good alternative to apply for modeling and calculation of the operating costs of a process.

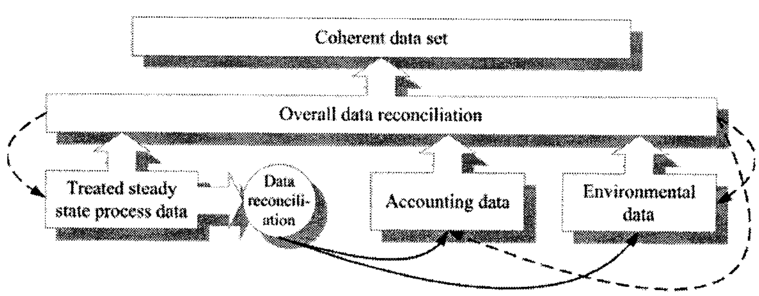

Figure 4: Data reconciliation of different types of data

3C Software [1] is widely used in the pulp and paper industry and uses an approach by which the accounting system can be easily integrated with e.g. process control systems or product tracking systems. Yeager [27] discusses the implementation and use of the 3C product at a fine paper mill. An ABC-like cost model is used which is based on an object-oriented design. Overhead costs are better allocated, product costs are traced more accurately and optional cost scenarios can be run that show the financial implications.

2.6 Life Cycle Assessment (LCA) aspects of business model

Life Cycle Assessment (LCA) is used for the modeling of the site-generic environmental impact of a product. LCA can be used to examine the environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, and disposal [10].

LCA is a chemical engineering tool since it relies heavily on mass and energy balances and can be used to establish critical environmental performance indicators. It has been applied in process selection, design, and optimization for identifying clean technologies [3]. LCA, when applied correctly, can yield the best process option from an environmental perspective [2].

In the context of process design, the main advantage of using LCA lies with the ability to analyze the environmental performance of a proposed design using a broader perspective than more conventional approaches, such as Environmental Impact Assessments (EIA's) which are site-specific. LCA has been used effectively in the pulp and paper industry for examining design options, for example in Salazar *et al.* [21].

In general, a life cycle thinking approach in the pulp and paper industry is oriented towards the use of an LCA baseline model as an engineering tool to analyze process variants. Specifically, the following applications are currently being investigated [22]:

- Use of LCA for the demonstration of continuous environmental improvement in the context of Environmental Management Systems,
- Use of LCA for the assessment of major process modifications in the context of Environmental Impact Studies (EIS's), and
- Use of LCA for the investigation of minimum impact manufacturing configurations in the context of strategic process planning.

New LCA-based continuous environmental improvement metrics related to process operations will be developed by comparing the results of the baseline model for mill process data from different years. For the two latter applications, LCA can also be used as a comparison tool in order to assess the environmental benefits and impacts due to the transition of the baseline process to novel designed mill configurations.

2.7 Supply chain modeling aspects of business model

A supply chain is a "network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer" [25]. Supply chain modeling is an approach to modelling the network (the supply chain) that exists between a manufacturing facility and its suppliers and customers. The benefits of supply chain modeling are manifold:

- Better understanding of the supply chain itself,
- Better understanding of the needs of the customer,
- Achieving a strategic fit between the supply chain and competitive strategies, which means that the supply chain capabilities should match the competitive objectives,
- Increasing the performance of the supply chain by looking at its efficiency (the cost of making and delivering a product to the customer) and its responsiveness (the ability to respond to wide range of quantities, meet short lead times, handle a large variety, innovate and meet high service levels).

The supply chain model is used in the analysis and optimization of product chains for obtaining a better material flow, and is therefore a tool for supply chain management (SCM).

The supply chain model uses data coming from the process, cost, and environmental models in order to assess the influence of changing operating conditions or changing process design on the material flow throughout the supply chain.

2.8 Using outcomes from the business model

The outcomes from the business model (cost, process and environmental) are to be used in decision analysis. In engineering, decisions made on a corporate or facility level are typically profit-driven. With the business model, a thorough analysis can be executed to make well-informed decisions that reflect the preferences of the decision-makers, done with Multi-Criteria Decision-Making (MCDM) techniques, for example Multi-Attribute Utility Theory (MAUT) which was developed by Keeney and Raiffa [12]. The trade-off between economic and environmental objectives can be determined by the assessment of decision weights.

2.9 Future possibilities

If such a business model were to be developed for a pulp and paper mill based on real-time cost, process and environmental data, the possibilities for its use in decision-making would be limited only by the imagination of corporate and mill management.
For example, incorporating variability or uncertainty in the data for decision making would permit design and operating decisions to be made based on operating parameter probabilities of occurrence and extreme values. Ultimately, the business model could evolve into a dynamic environment where decisions can be made in real-time using this data. For example, optimization techniques could be used to maximize the expected profit and simultaneously, to minimize the expected environmental impact for different operating regimes. Based on these calculations, design criteria can be defined such that Pareto-optimal regimes that simultaneously feature the highest profitability and the lowest environmental impact are maintained more easily.

Two other important issues that could be taken into account are the flexibility and feasibility of new process designs. A process design needs to meet feasibility criteria over a range of uncertain parameter values in order to guarantee safe and productive operations. In so doing, the flexibility of the process design needs to be taken into account as it indicates the capability of the process to achieve feasible operations. However, there is a trade-off between the flexibility and the cost of a process. This trade-off can be quantified with the business model.

The business model can be extended along the supply chain or a company-wide model can be constructed connecting several mills in one model. Flexibility and feasibility of the supply chain can thus be studied using real-time data and knowledge.

3. Process design decision-making: Hypothetical case study

In this hypothetical case study, the business model will be applied to a decision-making problem regarding process design changes at a hypothetical integrated newsprint mill. The specific problem will be a combination of the engineering of an existing De-Inked Pulp (DIP) plant with the goal of increasing DIP-production, and the implementation of an on-site cogeneration plant at this mill. This is a retrofit problem in which the consequences of both projects on the existing mill are considered from a process, economic, and environmental perspective. The existing mill consists of:

- 4 paper machines with a production of 1100 admt/day of newsprint paper,
- 2 Thermo-Mechanical Pulp (TMP) lines that produce 925 admt/day,
- DIP production of 175 admt/day.

The following process options have been defined:

- 550 admt/day DIP (1- or 2-loop configuration), 550 admt/day TMP, 30 MW cogeneration,
- 1100 admt DIP (100% DIP) (1- or 2-loop configuration), 14.7 MW cogeneration.

The design changes are subject to environmental and economic targets. The business model and decision-making procedure will be tools for choosing the most preferred design.

Figure 5.a illustrates the procedure for using the real-time data and the business model for process design decision making. This procedure starts with the treatment and reconciliation of the data. These data are then used by process integration tools in order to construct process design options. Scenarios are developed for each of the design options and the business model is run to assess the performance of the scenarios both economically and environmentally and optimize this performance. The knowledge obtained in this step is then used in a decision analysis in order to determine the most preferred design.

The case study described in this section serves as a proof-of-concept for the general procedure and is illustrated by the simplified method in Figure 5.b. The first step in the case study is to execute a classical techno-economic study and Environmental Impact Study (EIS) of the process options for increased DIP production and cogeneration. During the techno-economic study, sensitivity analyses are done. Key sensitivity parameters under review may be:

- DIP-plant: use of different technology (1-loop vs. 2-loop configuration), scale of operation, price volatility of waste paper,
- Cogeneration plant: use of natural gas vs. hog fuel,
- TMP-plant: amount and price of electricity used,
- Mill location: the location of the mill affects energy prices and transportation costs.

The characteristics of the developed process design options are transposed to the business model. The process is modeled based on first principles, the operating costs are modeled using ABC-like accounting principles. The environmental impact of the design options are modeled using LCA in order to also take into account environmental impacts due to the product chain.

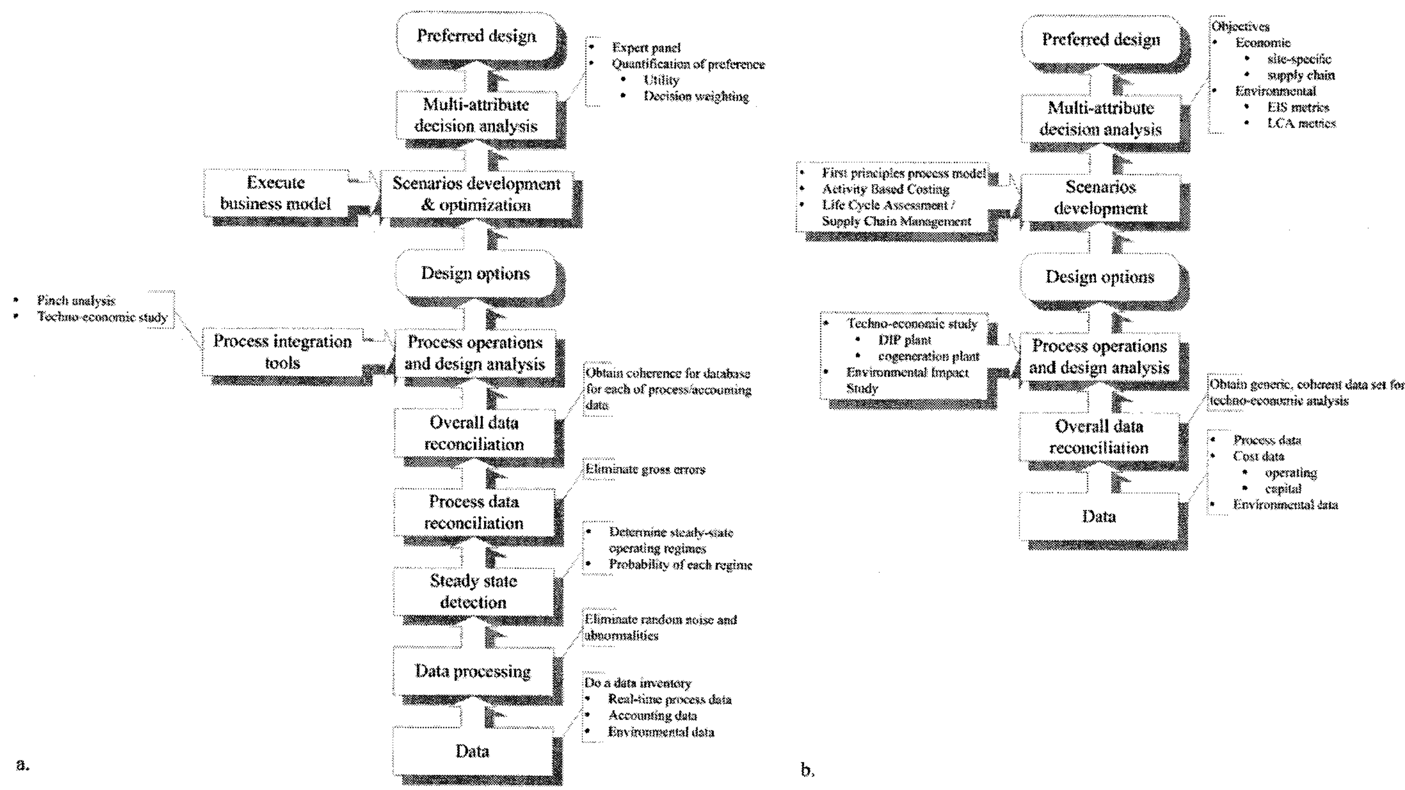

Figure 5: The "bottom-up" approach for using real-time data in process design: a. general procedure; b. case study procedure (proof-of-concept)

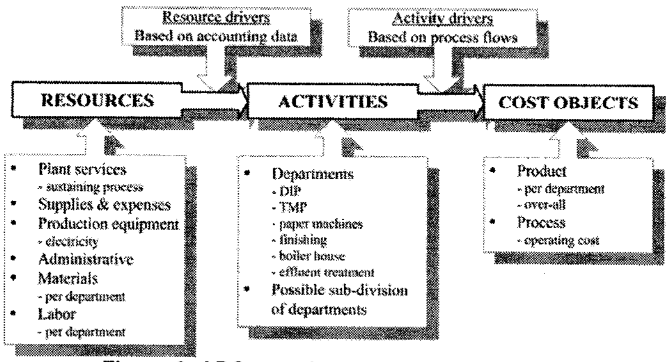

Figure 6: ABC at an integrated newsprint mill

Furthermore, impacts on the supply chain due to the different design options are assessed with the help of a supply chain model.

Linking process parameters to parameters in the ABC-like accounting model and baseline LCA model is clearly critical in order to have consistent outcomes from the business model. For the example of cost accounting, it is important to know how the cost model parameters change with a changing process design or product (Figure 6). For instance, the activity drivers, which are calculated with the actual flows in a process, will be based on this kind of information. As with the ABC model, process parameters also need to be linked to parameters in the LCA. The LCA gives a product-oriented view of the environmental impact and as such, it can be used to study the impacts of producing different products. Using scenario analysis, the flexibility of the process design is taken into account when ultimately deciding which design options to implement. For instance, ABC-like accounting can be used to calculate the marginal costs of running different scenarios with a given process design.

The decision structure for choosing the most preferred design is based on the trade-off between the economic and environmental objectives of the decision, as illustrated in Figure 7. Within each of these objectives, there are sub-objectives based on selected representative metrics. There are site-specific cost metrics (Net Present Value) and supply chain based cost metrics (e.g. transportation and inventory costs), as well as site-specific EIS-metrics (e.g. effluent concentrations) and more global and local LCA-metrics (e.g. respectively global warming potential (GWP) and acidification) for environmental objectives. The outcomes of the business model are used to determine these metrics.

4. Conclusions

In this paper, a framework was presented in which real-time process, cost, and environmental data can be used for process design purposes. A bottom-up approach, starting with these data and evolving to process design decision-making, was outlined and a hypothetical case study situated at a pulp and paper mill was used to illustrate its application.

It is clear that the implementation of information

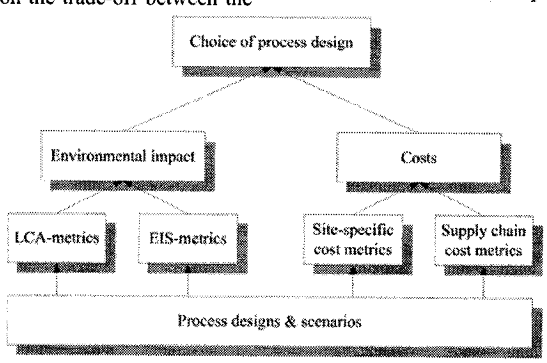

Figure 7: Decision structure for process design decision-making

management systems at pulp and paper mills has opened up opportunities for innovation by making available massive amounts of data. However, the full potential of this data is not being fully exploited. The proposed business model is based on real-time process data and a *bottom-up approach*. It uses a rigorous reconciliation of process, cost, and environmental data in order to relate the different sources of these data. By using a process model and linking it with an ABC-like accounting model, decisions can be made with which the marginal costs of the operations can be improved. Both LCA and supply chain management are used to determine the environmental implications of the product along the supply chain.

Using the business model for process design purposes has several benefits. By reconciling process, cost and environmental data simultaneously, clear relationships are constructed between the data and a coherent data set is formed. ABC-like accounting will provide a more detailed costing model for determining operating costs for different process scenarios. More global aspects such as supply chain issues and issues concerning global environmental impact (LCA) can be taken into account in the process design.

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B.4 Development of an operations-driven cost model for continuous processes – Part I: Framework for design and operations decision making

DEVELOPMENT OF AN OPERATIONS-DRIVEN COST MODEL FOR CONTINUOUS PROCESSES
Part I: Framework for design and operations decision making

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ABSTRACT
Given the increasing availability of reliable process and cost information, it is now possible to more accurately represent and reflect production processes for process design and operation. This paper presents a systematic methodology, established by collaboration between engineers and accountants, for developing a versatile tool to represent and understand the costs of complex production environments such as pulp and paper mills. The integration of process and cost information, contained in a "bottom-up" calculation engine, and the process-based aggregation of costs allow for easier modeling of complex cost relationships, by identifying how resources are consumed by activities and how activities are related to cost objects. Case studies for the application of the operations-driven cost modeling for retrofit process design and supply chain optimization are presented in Part II and Part III.

INTRODUCTION
As a consequence of the challenging business environment, Canadian pulp and paper companies have the difficult task of defining new business strategies to improve their competitive position over the longer term [1]. These strategies consist of increasing profitability either through the improvement of operational practices or by capital projects. Many pulp and paper companies recognize supply chain management (SCM) as one of the most promising solutions to preserve industry value, and to be better able to compete with global cost-effective producers on local and international markets [2]. In the case of capital spending projects, selection of the most profitable strategies for the modification of current manufacturing processes (retrofit design) is a critical challenge that must be addressed by the industry in order to adapt to the changing business environment and/or benefit from new opportunities during a prolonged period of limited capital expenditures.

The implementation of mill-wide data acquisition systems in the pulp and paper industry has opened the door to vast amounts of data from which information about processes and products can be extracted. Although this has enhanced *ad hoc* problem solving in mills [3, 4] and plays an important role in providing information to decision makers, a structured framework for advanced operations and design decision making support is needed in order to better exploit these data. As discussed by Lail [5], creating added value by systematically looking at the "obvious" – processes, knowledge and data available at the mill – is the key for successful supply chain projects and, we think, also for process design.

Even though many initiatives have been undertaken by process engineers, accountants, and information managers at mills, there is an important need for the development of best practices to help mills better use data for decision making. This paper presents an operations-driven cost model, established through collaboration between engineers and accountants, that integrates data across disciplines and mill areas, and considers cost accounting subtleties that can help mills to turn data into information aiding the decision making process. This paper first discusses the importance of the process perspective for cost management in continuous-process manufacturing. The bottom-up approach proposed by this work is described, followed by details of the operations-driven cost model. The model structure and data quality issues are discussed, as well as the potential for using this approach to add value to mill operations.

COST MANAGEMENT IN CONTINUOUS-PROCESS MANUFACTURING

It is essential to distinguish between accounting approaches often used at mills, and management-based accounting approaches such as the one presented in this paper. At mills, financial accounting can typically be characterized by the focus on external reporting (e.g. for shareholders) and on consistent representation of manufacturing costs over time. In the case of management accounting, the emphasis is to allow the analysis of historical cost data providing useful and relevant information for decision making, planning, control and performance evaluation [6]. It also recognizes the need to integrate cost information with production knowledge for more in-depth analysis and interpretation of the data.

Continuous process manufacturing has specific characteristics that have been identified and discussed by various authors (for the process industry in general [7, 8] and specifically for the pulp and paper industry [9, 10]). The direct application of cost management tools to the pulp and paper industry that have been primarily developed in the context of discrete-part manufacturing can be challenging and may not provide the expected benefits when applied to continuous manufacturing. It is critical to understand the specific manufacturing needs of a given process in order to develop management-based accounting tools adapted to a particular manufacturing environment.

As discussed by Reeve [8, 9], effective cost management systems for continuous process manufacturing must consider both the product and process perspectives. He recognizes the importance of process-related activities that often cannot be easily related to product strategy for the analysis and explanation of cost generation in mills. This is an essential distinction to make since, in most cost management approaches developed for discrete-part manufacturing, the product is considered to be the primary cause of activity generation within the plant. To better understand cost behaviour in pulp and paper mills, it is necessary to take into account the perspectives described as follows.

Product Perspective

In pulp and paper, similar to many continuous manufacturing processes, we can distinguish between two main types of operations: main processing operations (e.g. pulping and papermaking) and converting and finishing operations (sheeting, packaging, etc.) [11]. For discrete manufacturing, cost driver relationships within the plant are typically well explained using a product perspective. On the other hand, in pulp and paper, product-related activities are more useful to describe the cost behaviour of operations that are downstream of the main processing operations, where large product diversity is created. In fact, from the converting and finishing operations to the customers, a product perspective is adequate in order to evaluate the effect on cost of product specifications (trim, core, wrapping, labelling, etc.), channels (next-day delivery, direct shipment, shipment to distribution center) and customers (vendor-managed inventory, special contractual arrangements, etc). This is also the main reason why Reeve [8] suggested that, for continuous manufacturing, the implementation of traditional activity-based costing concepts should focus on the "demand side" of the supply chain.

Process Perspective

Particularly for main processing operations, it is often more relevant to consider the process perspective in order to be able to explain cost generation. Nevertheless, the process and product perspectives are not mutually exclusive and both perspectives may be required to explain some cost items, e.g. although transition costs are sequence-dependent - product perspective, batch-level – the explanation of the costs incurred requires an in-depth process analysis using a process perspective.

Production Process – A large part of indirect manufacturing costs at mills are caused by activities such as maintenance, that are more related to the production process itself than the product manufactured. Since these cost items are normally allocated to products, it does not provide any useful insight for cost management and continuous improvement [8]. Instead, cost driver relationships should be identified based on the analysis of process-related aspects such as maintenance and operating policies. In addition, the production process perspective is also necessary to understand how process activities generate cost within the main processing operations. It provides key information about the configuration of the process, the important flows, the type of processes involved (mixing, heating, reaction, etc.) and other relevant qualitative and quantitative inputs that may be required to characterize the structure of the manufacturing process.

Operating Conditions – In discrete manufacturing, it is relatively easy to calculate direct manufacturing costs because it is usually possible to measure the level of activity and resource consumption for each particular unit, and also because these activities can be traced to the final product (via routing and bill-of-material). In continuous processing, operating conditions at each step of the process are responsible for resource consumption. Even though they can often be measured with some precision, it is often not feasible to keep track of the resources used with the principal flow of material. Thus, for simplicity, product homogeneity is assumed [12] and the costs are calculated based on standard recipes. These specify raw material usage (additives, chips, energy, etc.) as well as target operating conditions for producing the final product within the required specifications. The resulting cost information does not correspond to reality, and variance analysis only provides aggregated information that fails to give the required visibility for decision making. Given the variations within the manufacturing process, the real operating conditions are not fixed to the standard levels and should be used to analyze direct manufacturing costs. Contrary to discrete-part manufacturers, the development of a cost management framework for continuous processes should emphasize the use of process variables to characterize cost generation within the plant [8], particularly for the main processing operations.

While it may seem natural for process engineers to consider these aspects, they are generally not understood or recognized in the cost management literature, and have not yet been commonly applied in cost systems that are implemented in the pulp and paper industry.

The development of new costing models in the 1990s focused on overheads and business processes, and little attention was paid to primary activities in complex manufacturing environments. Thus, simplified approaches are used for the treatment of direct manufacturing costs and operational activities [13]. For the pulp and paper industry, this treatment is a critical issue since direct manufacturing costs are charged to the product based on a more or less systematic approximation of the process conditions and process-related activities in the mill. Similar to the discussion on overheads that led to the development of activity-based costing in *The hidden factory* [14], the pulp and paper industry uses methods (e.g. standard costing) to relate direct manufacturing costs to product, but these methods do not provide a useful explanation about how costs are really generated within the main processing operations. Technological challenges as well as the lack of guidelines and systematic methods have constrained the industry from addressing this data-intensive challenge. However nowadays with the advent of information management systems (IMS), this challenge has become less restrictive. Using systems-oriented and multidisciplinary approaches, it is now possible to analyse process and cost data in an integrated manner in order to better understand the main processing operations. This would not only provide an improved basis for cost management, but would also help with the application of higher-level decision support tools such as supply chain optimization or multi-criteria decision-making for retrofit process design.

OBJECTIVE

The primary goal of this study was to develop a framework for creating an operations-driven cost model that integrates process and cost information in order to characterize the manufacturing costs of the processing operations in pulp and paper mills. Specifically, the three following requirements were considered for the elaboration of the cost model:

1. It should emphasize a bottom-up thinking where, rather than providing aggregated cost information, the information coming from the process can be systematically integrated to better reflect the capability of the main processing operations.
2. Given their importance in pulp and paper mills, the approach should also include a structural element to incorporate overhead costs within the model.

3. The framework should not be problem-specific. An approach should be used in order to represent various processes in order to provide a general framework for process operations and process design decision making.

More generally, the aim of this work was to discuss how process systems engineering tools, which emphasize visibility of information and structural flexibility, can help to manage, analyze, and interpret information to support decision making for process design and operation.

"BOTTOM-UP" APPROACH

The process-based business modeling approach [3, 15, 16] , schematically represented in Figure 1, is based on "bottom-up" or "operations-driven" thinking, consisting of using lower-level process data and detailed process analysis to better reflect manufacturing capability for higher-level decision-making. Therefore, the overall approach aims first to characterize the manufacturing operations (descriptive) and second, at providing advanced decision support (prescriptive). To achieve these goals, four main steps are considered: data acquisition, systematic analysis, process and cost modeling, and decision-support modeling. Process and cost data, typically provided by information management systems at mills, may come from various sources such as process simulations, general ledgers, etc. Many tools and approaches can be used to collect, treat and analyze these data, in order to extract the necessary and relevant information for decision making. The operations-driven cost model is the central element where cost and process information are captured and systematically integrated to characterize the continuous processes. Due to its structure, the cost model can be used to support either design or operational decision processes. For example, in the case of operations, it can be used to support supply chain optimization whereas in retrofit design, it can be used to support a multi-criteria decision making process for evaluating different design options.

OPERATIONS-DRIVEN COST MODEL

Process and cost information must be integrated and linked to the manufacturing processes at the mill and ultimately, the cost object. The *cost object* is defined by the functional unit for which the cost is measured. It can be an activity, a product, a process, a service, a division, etc. Activity-Based Costing (ABC) is now a well-known method that was developed for modern manufacturing environments with the goal of demystifying overhead costs that were traditionally assigned to cost objects using inappropriate allocation bases [17]. The principle of ABC consists of modeling the usage of resources by activities performed, as well as the activities required by the cost object. Although this approach traces overhead costs to activities, the relationships used in ABC-based cost systems to link primary

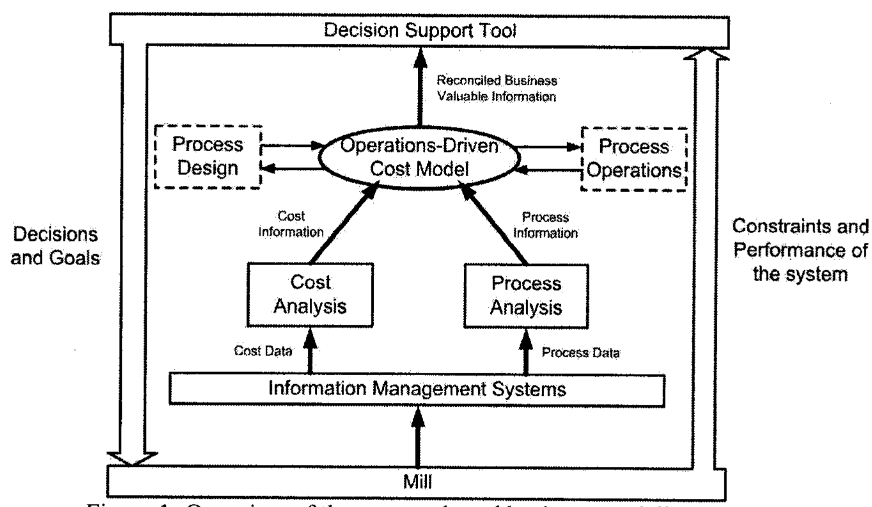

Figure 1: Overview of the process-based business modeling approach

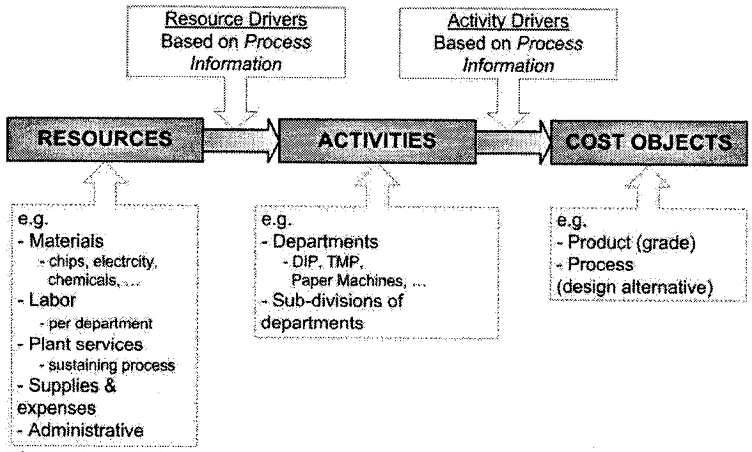

Figure 2: Relationship between resources, activities, and objects in ABC

resources (direct manufacturing costs) to cost objects are often too simplistic (e.g. direct charges) and are inappropriate for consideration in continuous process environments. Nevertheless, the ABC approach provides important extensions [18] to traditional costing systems, that are particularly relevant for the elaboration of an operations-driven cost model in pulp and paper:

- Use of activities and processes as the focus of cost systems,
- Tracing the cost of using the resources,
- Using a richer set of cost drivers (based on observable measures) to reflect operational complexity.

By using "bottom-up" process and cost information, resource and activity drivers can be identified and mill-wide correlations can be reflected to characterize cost generation within the mill's main processing operations (Figure 2). Therefore, the operations-driven cost model is based on "ABC-like" principles that incorporate and emphasize the importance of the process perspective as a source of costs, which allows production managers to better track and control their costs. As mentioned earlier, cost modeling of continuous processes needs to consider both the design of the manufacturing processes and the specific operating conditions used to manufacture different products. In this context, the following elements must be introduced in the cost model:

1. The *cost center* corresponds to a collection of physical process units that represent part of the manufacturing process. The routing of these cost centers, and the specification of the equipment used, is defined by the process design. The level of aggregation of the various cost centers has to be determined with respect to the type of decision that is to be made using the overall business model approach.
2. *Activities* refer to the operating conditions at each of the *cost centers*, e.g. running a pump or a heat exchanger, drying pulp or paper, etc. They are characterized by *process information* resulting from a systematic bottom-up analysis approach, e.g. flow rate, consistency, temperature, and pressure, or other physically measurable process variables.

Within the operations-driven cost model, *cost centers* and *activities* are considered together in an element called the *Process Work Center (PWC)*. As shown in Figure 3, a mill is represented by a group of *PWC*s that are arranged in series and/or in parallel. An *Overhead Work Center* is also introduced for modeling production overheads and non-manufacturing costs because they must be treated differently from a computational standpoint. When the cost model is calculated, the costs flow between the *PWCs* as defined in the model, and accumulate in the *Overall Cost Object.* This final *cost object* can for instance be the product cost for different operating conditions of a given design or for process design alternatives.

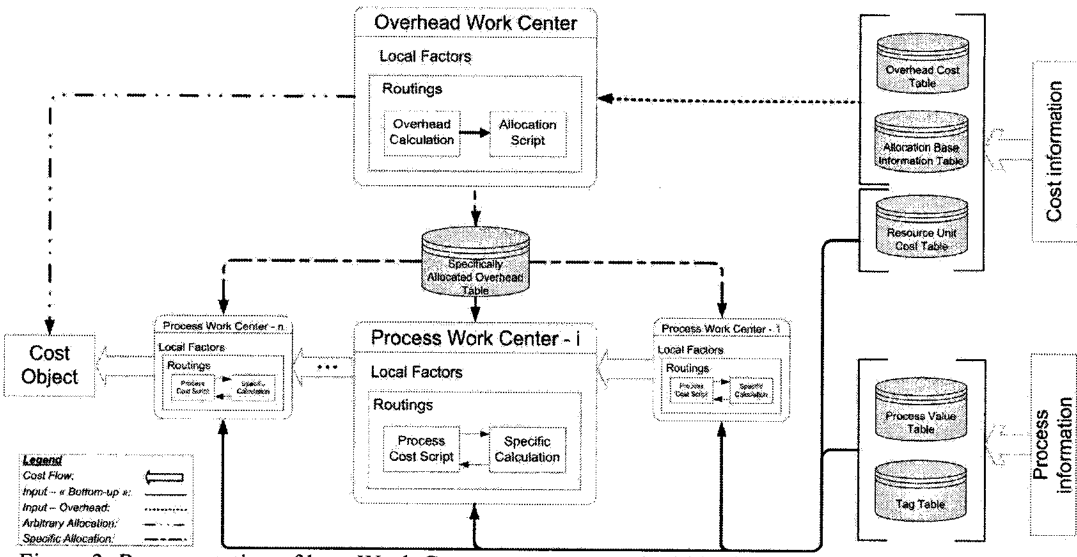

Figure 3: Representation of how Work Centers are structured within the operations-driven cost model

The operations-driven cost model in this study was developed using the Impact:ECS^{TM} software package from 3C Software Inc (Atlanta). This tool is particularly well adapted to the needs of complex production process environments, such as those in the pulp and paper industry, and it has been adopted by several leading pulp and paper companies. Its underlying platform, based on a relational database, allows for an efficient structure and management of process and cost information flows within the model. Moreover, the flexibility of Impact:ECS^{TM} provides the ability to customize the storage of data, the calculation execution order, and the structure of the model [19, 20].

PROCESS WORK CENTER

One of the key elements of the cost model is the structure used to represent main processing operations at the mill. A generic framework was developed that permits the *PWC* to accommodate the cost flow along the process, the bottom-up feeding of process information, the need for flexible specific calculations, the assignment of overheads, and a standard process-based cost calculation. This structure consists of two main sections, i.e., the local factors and the routings (see Figure 4). Local factors are units of information that are specific to or characteristic of a *PWC*, and can be accessed only by operations called for in the *PWC* in which they reside. They can be classified into three groups: *Work Center Characterization*, *Specific Information*, and *Reporting*.

- Within the first group, local factors permit the introduction of general information needed to define a particular *PWC* e.g. the name, the reference flow as well as the overall product reference flow. Different scenarios can also be considered using binary parameters.
- The role of the second group ("Specific Information") is to allow the user to interact with the inputs of the specific calculations (to be further discussed later).
- The third group of local factors is used to report information. It provides quick access to the main results and important outputs when the calculation is done.

The *PWC* structure has multiple routings that define a step-by-step approach to the functions that have to be performed during cost calculations (Figure 4). This ensures a structured flow and logical treatment of information throughout the model. The first routing, *Cost Flow In*, establishes the calculation order by enforcing the precedent *PWCs* to compile before. It also pulls the previously calculated cost information within the current *PWC*. The second routing, *Process Information*, loads and stores the information coming from the *Process Value Table* that contains all "bottom-up" data that are used to characterize the particular activities that are accomplished in the *PWC*. It is also possible to add or

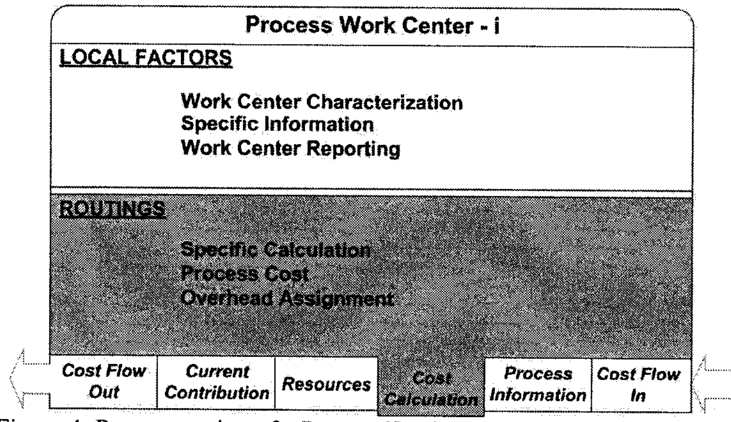

Figure 4: Representation of a Process Work Center within the cost model

modify process information in order to perform a sensitivity analysis. The main routing, *Cost Calculation*, dictates how the process, overhead, and cost information are structured and how the *PWC* is calculated. It consists of four sections: *Initialization*, *Specific Calculation*, *Process Cost*, and *Overhead Assignment* (see Figure 4). Except for specific calculations, the three sections are generic, regardless of the *PWC*. The fourth and the fifth routing, *Resources* and *Current Contribution*, are used mainly for reporting purposes. *Resources* displays the results for each step of the cost calculation, in an ABC-like fashion where the relations between resource consumption, activities performed, and the *cost object* are shown. *Current Contribution* aggregates all the cost information obtained from the previous and the current *PWCs*. This aggregated information is then available for the routing *Cost Flow Out* and also for the local factors (under *Reporting*). Finally, *Cost Flow Out* takes the aggregated cost information and makes it available for other subsequent *PWCs* in the model.

Cost calculation routing

Process cost

Process cost, which is at the heart of the *PWC,* performs the generic cost calculation using the ABC-like approach discussed earlier. This is used to establish engineering-based relationships using mass and energy balances, for resource consumption within the mill. Given specified local factors (e.g. tags to consider), and since the appropriate cost drivers come from "bottom-up" approach (*Process Value Table*, based on process information), both the production process and the operating conditions are systematically considered for cost calculations. Figure 5 illustrates the structure and how the information is managed within the *Process Cost script* that integrates five important elements: the *Local Factors*, two routings of the *PWC* (*Process Information,* and *Process Cost)*, the *Tag Table* and the *Resource Cost Table*. More precisely, the script consists of the following steps:

A. Information characterizing the current *PWC* is extracted from local factors.
B. Using this information, the script can search within the *Process Value Table* and the *Process Information* routing for process information linked to resources and reference flows relevant for the calculations.
C. After obtaining the process information, the particular type of resources associated with each element classified as a resource needs to be identified. The tag identification number of the element is used to acquire the resource identification number from the *Tag Table*.
D. Given the type of resource, it is then possible to obtain, from the *Resource Cost Table*, the unit costs for each of the resources considered.
E. When all the relevant information has been gathered, costs are calculated within the script using an ABC-like structure that uses a combination of drivers to relate the resource consumption to the final cost object. First, the unit costs are multiplied by the resource driver that determines the consumption rate of a particular resource for a given reference flow, which is most closely related

to the resource (e.g. n kg of chemical per BDMT of chip). Then, using an appropriate combination of reference flows, the consumption of the resource is linked to the *PWC*. It provides the cost of the resource consumed given the *PWC* reference flow. Finally, using the ratio of the *PWC* reference flow to the overall product reference flow, the costs are attached to the final cost object.

F. The results of the different steps for the *Process Cost Script* are displayed within the *Reporting* section of the local factors and stored in the *Resource* routing.

Overhead Assignment

Some overhead items can be assigned to each of the *PWCs* based on specific rules. Thus, the main purpose of this script is to integrate information needed to provide the required visibility of the portion of the overhead that can be traced to the production process. Since there is no overhead calculation done locally in the *PWCs*, *Overhead Assignment* extracts and integrates the particular cost information that has been treated by the *OWC*.

Specific Calculations

The aim of the operations-driven calculation engine is to be as generic as possible in order to be applicable to any type of process. At the same time, every manufacturing process is unique. The cost model structure needs to have enough flexibility in order to be able to address such specific calculation requirements. In fact, the underlying process structure is always valid, but in some situations, it is necessary to perform preliminary "side-bar" calculations to fit the standard structure. An example of a specific calculation is to transform the units of a flow rate from l/min to kg/min, or to calculate the mass flow rate in BDMT/h using the flow rate in l/min and the consistency of the flow. In any case, it is preferable to use a preformatted user-friendly calculator that allows for easy build-up of a series of simple commands that need to be performed. Using this approach, it is very convenient for users to view, understand, and modify calculations.

Illustrative example

The operating cost of a reject refiner is calculated using the operations-driven cost modeling approach (see Figure 5). First, relevant process information is gathered for the *PWC* "pulp cleaning". The values gathered at five data acquisition points (so-called "Tags") are the results of a process data analysis. This process information is then stored and classified in the Process Value Table using a systematic method based on a traditional process unit representation. Every entry within this table specifies the attached *PWC*, the tag identification number, the process value itself, and the units. For each element within the table, we also differentiate between a resource, a reference flow, a *PWC* reference flow, or a product reference flow (see the description of tags in Figure 5). Two specific calculations are done to determine the mass flow rate to the reject refiner. Then, using the information from the *Process Value*, *Tag* and *Resource Unit Cost* tables and the specific calculations, the *Process Cost* script (as described earlier) calculates the cost in $/BDMT for the reject refiner under the given process conditions. The resulting cost information is reported in the local factors and added to the cumulated pulp cleaning cost.

OVERHEADS WORK CENTER

The *Overheads Work Center (OWC)* is included to estimate the mill burden, or indirect manufacturing and non-manufacturing costs, within the cost model. The structure developed for the *OWC* (see Figure 6) is significantly different from the *PWC*. Although local factors have a similar function, the main differences reside in the structure and utilization of routings. The *Overhead Cost* routing is the principal component of the structure. It is used to manage overhead-related information as well as to structure the calculations. First, the accounting period associated with the overheads is set. Then *General OH Calculation* determines an hourly rate for each overhead item as well as the general aggregated overhead cost for each category defined in the accounting system of the mill. Using the allocation base information available, each item considered is classified into either one of two groups: items that can be specifically allocated, using precise information on how resources are used, to a *PWC* (e.g. supplies, maintenance, labour, etc.) and items that are arbitrarily allocated to the final cost object (e.g. insurance,

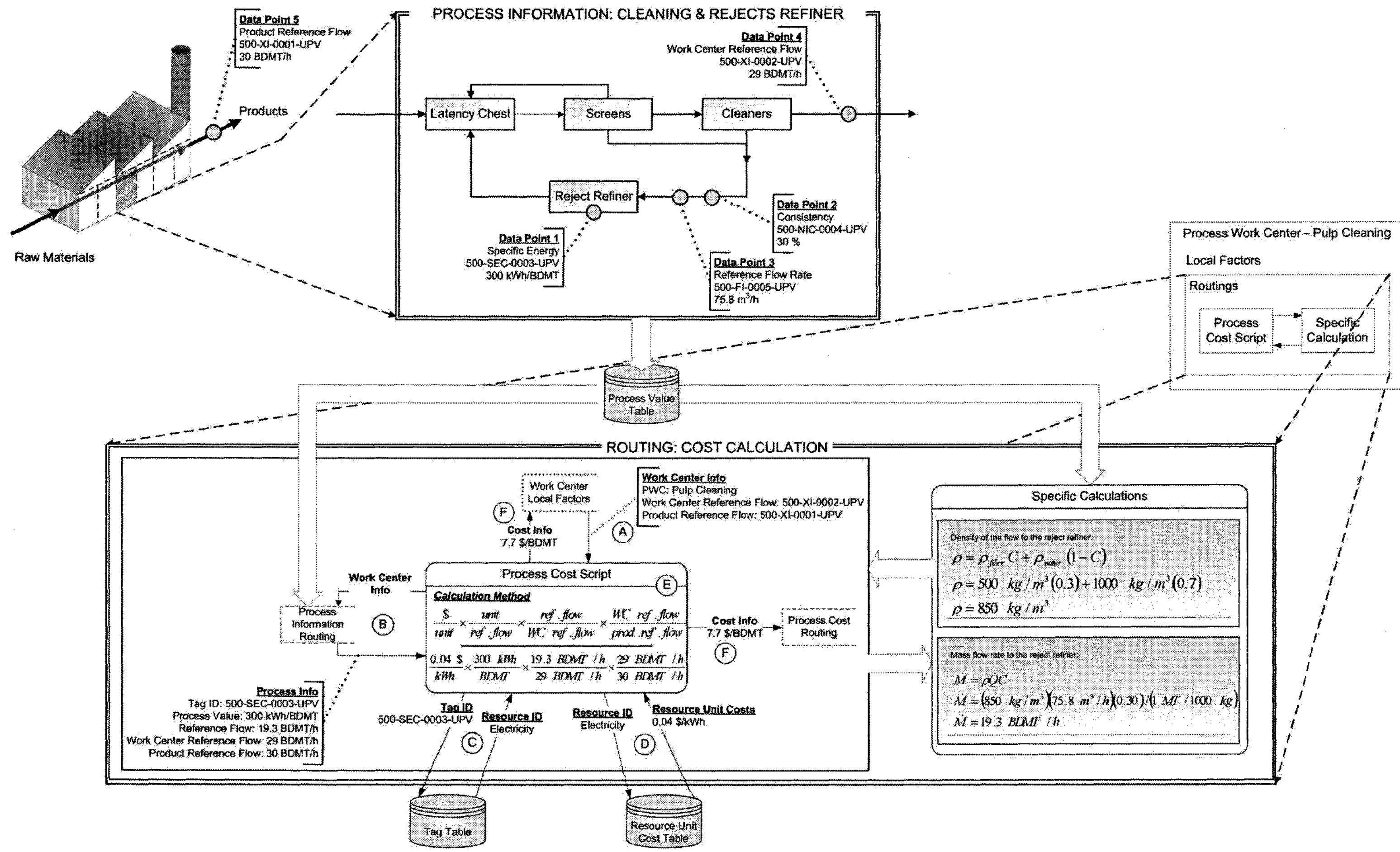

Figure 5: Process-based work centers for calculation of the reject refining operating cost

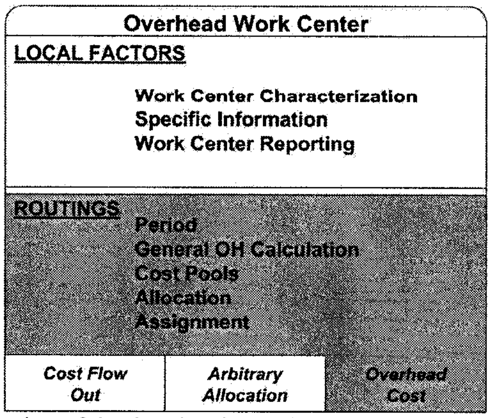

Figure 6: Representation of the Overheads Work Center (OWC) within the cost model

administration). *Cost Pools* aggregate the cost items of the first group that have the same allocation base and, within *Allocation*, distributes them among the *PWCs*, depending on their share of this allocation base. *Assignment* loads the results in the *Overhead Table* described earlier, which is called by the *PWCs*. Finally, the *Arbitrary Allocation* routing is responsible for the aggregation of the costs of all items that have to be allocated to the final cost object. This information is then transferred directly to the cost object using *Cost Flow Out.*

EXAMPLES OF APPLICATION RESULTS

In this section, we present examples of results obtained by the application of the operations-driven cost modeling approach in the context of both process design and operations. These results are only briefly described and the authors refer to Parts II and III for a more detailed description.

Operations

The aim of the cost model development is to characterize the direct manufacturing grade costs of a BCTMP pulp mill in order to support a bottom-up supply chain planning approach where manufacturing capability is determined using lower-level process data. Given the supply chain perspective, a relatively high-level model was developed by primarily considering the main manufacturing activities i.e. the pulping process. Seven *PWCs* were used to describe the operations and 30 tags were selected from the process data historian at the mill to characterize the cost model drivers (resources and activities). The corresponding process data, for a period of three months, were treated and stored in a relational database and integrated with other relevant mill information (e.g. production schedules). The analysis of the data, accomplished using queries, statistics and visualisation tools, allows for the identification of resource consumption patterns that are different compared to the standard recipes. The data describing these patterns, or so-called process information, are used as inputs to populate the different parameters of the cost model. Figure 7 shows the direct manufacturing costs calculated using the operations-driven approach, for each production campaign of a given pulp grade. Since fibre supply is an important supply chain decision variable, the cost of fibre is not taken into account within this model but rather, this cost is optimized within the supply chain problem. As shown, the results of the operations-driven cost model provide an interesting perspective compared to standard and actual costing approaches. Since cost drivers are calculated using historical process data and consumption patterns may have some similarities with recipes, the operations-driven approach is considered as being in between the standard and actual costing approach. Nevertheless, the real advantage of the proposed approach is the use of available process data with an ABC-like approach to identify, analyse and interpret the cost implications of various consumption patterns within the mill. This is much more consistent with managerial accounting and should be used as a basis for performance assessment and continuous cost improvement at the mill.

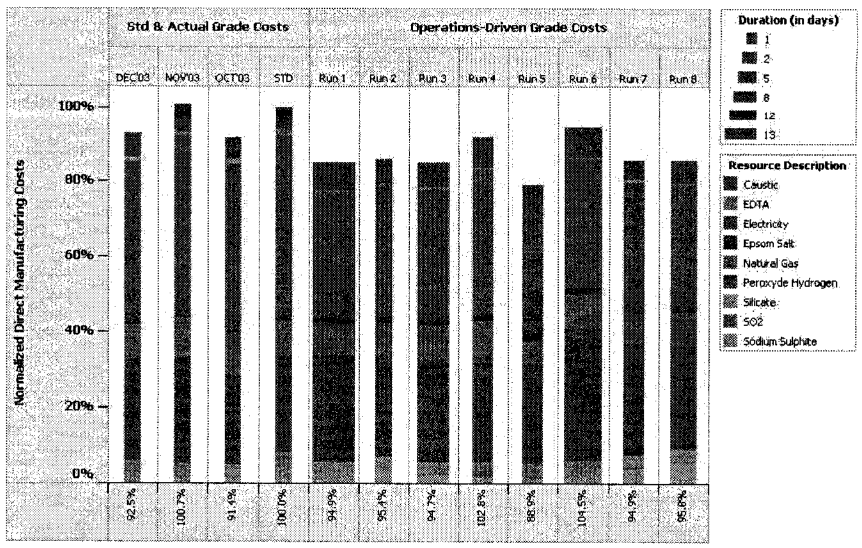

Figure 7: Application for operations: grade cost analysis for a BCTMP pulp mill

For continuous processes, such as a pulp mill, it is essential to consider the process perspective and the operations-driven approach, using process and mill data, is the key to better understand the generation of costs within the mill and to provide the required visibility of the cost performance of the manufacturing operations for supply chain planning.

Retrofit Design

In this case, the operations-driven approach is applied in the context of a large-scale retrofit design problem. The aim is to better quantify cost implications of several retrofit design alternatives for increased deinked pulp production and cogeneration at an integrated newsprint mill. For each design alternatives the capital costs and mass and energy balances were calculated. These data were used by the operations-driven cost model that was developed to evaluate the operating costs and profitability of the alternatives. Figure 8 presents the direct and indirect manufacturing costs obtained for the existing mill and each alternative considered. The colors represent the various *PWCs* considered for the analysis and the negative costs indicate either an income (e.g. cogenerated electricity sales) or a transfer (e.g. overhead outside the mill). One of the main advantages of using the operations-driven approach for retrofit design is the efficient and transparent evaluation of manufacturing costs based on a systematic description of the consumption of the resources by the *PWCs*. For example, in Figure 8, the higher manufacturing cost for the paper mill *PWC* can be traced back, using process information, to higher steam prices and thus, increased use of natural gas (as opposed to wood waste). The variation of overheads per alternatives, that is small compare to direct costs, are caused by a number of factors such as differences in maintenance material, tax credit, etc. This indicates that, even though overheads should be taken into account within the overall design process, it may not be an important factor to differentiate between the proposed alternatives. Finally, compared to traditional techno-economic studies, the operations-driven approach is better able to examine critical design variables and operating variants. Important *PWCs* can be identified and the changes in cost per activity in the *PWCs* can be assessed efficiently.

DATA QUALITY AND MODEL STRUCTURE

In order to construct the cost model, different sources and types of information must be considered. The relevance of any individual data stream, for the decision making process, tends to fall within the realm of judgement. Even though companies recognize the importance of system integration, data often comes

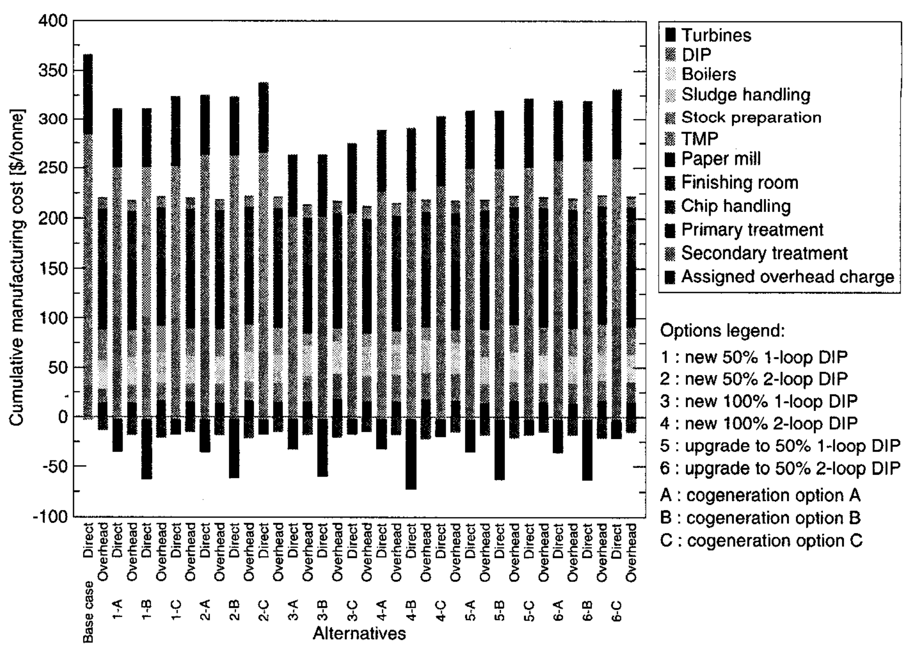

Figure 8 : Application for retrofit process design: manufacturing cost per design alternatives

from a variety of sources with different degrees of reliability, e.g. the accounting system, the process information management system, the laboratory information management system, spreadsheets, etc. The integrity and the nature of the data must be carefully assessed before they are used. Moreover, to address uncertainty in the data, sensitivity analysis is used to identify the elements that have the greatest impact on the model output and thus, require specific attention from the decision maker.

Even though, the integration and the relational analysis of the process and cost information are key elements of the multidisciplinary cost model, a similar approach could be developed using non-relational spreadsheets. However, compared to more sophisticated tools like Impact:ECS^{TM}, the flexibility and capability of the analysis would be reduced and the opportunity to leverage large amounts of information into valuable outputs for decision-support would be more difficult to realize. It would also be more challenging to manage the information across many process design alternatives and also, in the operational context, to maintain the integrity of the cost model over time.

IMPLICATIONS OF THE OPERATIONS-DRIVEN COST MODEL

The cost model presented in this paper has the following advantages:

- The integration of process and cost information, the "bottom-up" calculation engine, and the process-based aggregation of costs allows for a more in-depth description of continuous processing operations. This, along with the use of the ABC-like concepts, provides a tool to better understand costs within the complex environments of pulp and paper mills. It increases visibility of the process perspective, and traces direct manufacturing costs more precisely than typical cost systems. As shown by the application examples, this improved characterization of manufacturing operations provides information that can be used in the context of retrofit design and supply chain optimization.
- The *PWC* structure, which is the basic element of the process-based business model, provides a versatile tool for representing industrial manufacturing processes. It is built to match the common definition of a process unit, and specific calculations can accommodate particular cases.

Furthermore, the structure can be used to represent and analyze different operating conditions (regimes) and design alternatives.

- Compared to typical ABC approaches where observable measures (used to analyze activities) are determined by interviews and surveys, the operations-driven approach uses data that are typically available at mills. This is a significant advantage since it provides a reliable source of information that requires minimum effort to obtain. Also, with the integration of process and cost information, the model can serve as a basis for the comparison and the reconciliation of information coming from different sources. For example, the grade cost information obtained with this model can be compared with actual and standard costs. In the context of process design, it helps to keep process and cost information synchronized; this is an improvement of the traditional process design in which the process and cost models are typically maintained separately.
- Since the costs are easily traceable to process unit operations, significant benefits can be achieved if the model were to be used and maintained by process/operation engineers who have the ability to control or act on costs incurred during production. The work presented in this article tries to define new guidelines for a better use and integration of available cost and process data at pulp and paper mills.
- If continuously used at a mill, the proposed model could be the starting point for addressing operational and design problems using the same framework. It provides a more consistent model that can be used or adapted for different kinds of questions, instead of building new models for new problems.

CONCLUSIONS

With the advent of information management systems, the pulp and paper industry has the opportunity to extract additional value from data by using tools such as the proposed operations-driven cost model, and to use the generated information for improved decision making. The principal challenges of this approach are not related to information technology itself, but rather to the designed approach integrating the following elements: 1) understanding the available tools, 2) understanding the business and manufacturing processes, 3) developing new and specific methods, frameworks, and models and 4) understanding the needs of the decision making activities.

Case studies for the application of the operations-driven cost modeling for retrofit process design and supply chain optimization are respectively presented in Part II [21] and Part III [22].

ACKNOWLEDGEMENTS

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B.5 Potential cost benefits of electricity load shifting when designing upgrades to an integrated newsprint mill

POTENTIAL COST BENEFITS OF ELECTRICITY LOAD SHIFTING WHEN DESIGNING UPGRADES TO AN INTEGRATED NEWSPRINT MILL

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ABSTRACT

This article describes the application of an operations-driven cost model for assessing the potential benefits of electricity load shifting in a TMP plant when designing upgrades to an integrated newsprint mill. The case study considered several retrofit design options for the upgrade of the mill by increasing deinked pulp (DIP) production and implementing cogeneration. Identifying the optimal load shifting profile resulted in an increase in the project NPV of $21 to $27 million depending on the alternative. Sensitivity results show that considering load shifting in the design process may in some cases alter the best design choice. This is more likely to occur at high average electricity prices and a large difference between on- and off-peak electricity prices. Furthermore, applying load shifting when considering real-time prices reduces manufacturing costs with $2500/tonne when compared to the existing mill, at an extreme electricity price of $1045/MWh.

BACKGROUND

Retrofit design at an integrated newsprint mill

The availability of process and cost data through the implementation of Information Management Systems (IMS) at pulp and paper mills has grown at a tremendous rate in recent years. These data have helped mills to better understand and troubleshoot their processes. However, a recent survey on the use of IMS at North-American mills revealed that these data are not fully exploited [1].

Retrofit process design is one of the applications that may benefit from the smart use of the available data by employing new modeling approaches, analysis tools and methodologies in order to make better design decisions [2]. An operations-driven cost modeling approach has been developed that focuses on the mill processes themselves rather than on the product as is usually done using more traditional costing approaches [3]. This approach has already been used in a design context for better characterization of an existing mill and a number of retrofit design alternatives, and for a more in-depth analysis of these alternatives using marginal cost analysis [4].

Although a number of techniques are available for reducing TMP energy consumption, they yield only marginal reductions when compared to the implementation of de-inked pulp (DIP) production to replace TMP (assuming a constant newsprint production rate and transaction price). Such modifications have a dramatic effect on mill-wide energy consumption. By decreasing TMP production, the production of steam from the TMP plant (required principally for paper drying operations) is reduced. The mill must compensate for this loss of steam by increasing the steam production in the steam plant. Consequently, this increase can give rise to capital expenditures and consideration of cogeneration at the mill. Cogeneration is the combined production of electrical (or mechanical) and useful thermal energy from the same primary energy source [5].

Electricity load shifting as operational strategy

An increasingly important strategy to reduce power costs at an integrated newsprint mill is the scheduling of the TMP plant's electrical load. Electricity load shifting refers to the scheduling of the electricity load in such a way that electricity use is diverted from on-peak to off-peak electricity price periods [6]. Roussel [7] describes a system that monitors power consumption to enable several mills to match fluctuating energy market prices and the availability of energy. The system gathers current energy market information, weather data, and data about power usage at the mills. Using this information, the mills can plan their daily load in a planning module. When the price is high, a mill can elect to shut down some equipment or the entire mill, and they can sometimes sell their power generation back to the grid, or even potentially be reimbursed for curtailment of power demand. This also leads to improvement of the profitability of the operations by means of optimizing the electricity load profile [8,9].

Load shifting is of particular interest for a TMP plant, since mills can often negotiate different electricity rates for on-peak and off-peak periods. Consequently, determining the optimal load shifting strategy may have a significant and positive impact on costs at integrated newsprint mills. Electricity load shifting may help a mill to avoid production at time intervals with high electricity prices that are characteristic of a deregulated electricity market. However, this requires a surplus of pulp production and storage capacity. The potential for load shifting benefits increase with increasing storage capacity [10].

OBJECTIVES

This paper seeks to demonstrate the use and application of the operations-driven cost modeling approach (as discussed in [3]) to a retrofit design problem using the data and structure of an ABC-like cost accounting system. The objectives of this work were as follows:

- To evaluate retrofit design alternatives for increased DIP production and cogeneration [11] using the operations-driven cost modeling approach,
- To incorporate a model in the operations-driven cost model that describes electricity load shifting in the TMP plant,
- To obtain better insight into the design alternatives using the cost model by considering electricity load shifting.

BASE CASE MILL AND DESIGN ALTERNATIVES

Existing mill configuration

The existing mill on which this study is based consists of the following production units:

- 4 newsprint machines with a total average production of 1100 tonnes/day of newsprint,
- 2 TMP lines with a total average production of 925 tonnes/day of pulp,
- A DIP plant with a total average production of 175 tonnes/day of pulp, where 85% of the wastepaper used is old newspaper (ONP) and 15% is old magazine paper (OMG).

Furthermore, the following supporting processes are part of the base case mill configuration:

- A wastewater treatment plant that processes 50,000 m^3/day,
- A boiler plant that produces 7850 GJ/day of steam,
- A back-pressure turbine that generates only 0.4% of the total electricity demand of the mill.

De-inking and cogeneration design alternatives

The DIP plant process design configurations considered, had capacities of 550 tonnes/day or 1100 tonnes/day (representing a 50% or 100% DIP integrated newsprint mill, respectively) (see Table 1). Both the 1-loop and 2-loop DIP technology were considered, the 1-loop technology being more prevalent in North-America and less costly. The 2-loop DIP technology was considered to account for that fact that the quality of the waste paper basket is expected to deteriorate in the future [12]. The cogeneration configurations had the following characteristics (see Table 2):

- Increased wood waste capacity by the installation of hog fuel boilers,
- Reactivation of turbines that are currently idle and implementation of new back-pressure turbines or condensing turbines.

In total, 18 alternatives were analyzed in this case study by considering all combinations of the DIP and cogeneration configurations. The following naming convention for the design alternatives was used:

Table 1: DIP plant configurations

Option	Configuration
1	New 550 ADMT /day DIP plant, 1-loop
2	New 550 ADMT /day DIP plant, 2-loop
3	New 1100 ADMT /day DIP plant, 1-loop
4	New 1100 ADMT /day DIP plant, 2-loop
5	Increase to 550 ADMT/day by adding a second line to the existing plant, 1-loop
6	Increase to 550 ADMT/day by adding a second line to the existing plant, 2-loop

Table 2: Cogeneration configurations

Option	Configuration
A	One natural gas boiler is converted to burn wood waste, and existing backpressure turbines kept in service.
B	New wood waste boiler (at VHP) is installed. Half the boilers are upgraded to VHP operation. New backpressure turbine added.
C	New condensing turbine is installed.

Alternative {DIP configuration 1 to 6 as per Table 1}-{Cogeneration configuration A, B, or C as per Table 2}.

Impact of electricity load shifting on the mill energy profile

Table 3 gives an example of the changes in the mill-wide energy profile of an integrated newsprint mill when a load shifting profile is implemented. This example is valid for a design alternative where the TMP and DIP pulp production ratio is 50:50, when load shifting has a good potential for increasing the profitability of operations. When the TMP plant is shut down, there is no TMP steam production and the boiler steam use (i.e. steam produced in the boiler plant) increases. Therefore, more boiler plant generated steam is used in the process. Consequently, there is less steam available for the turbines to generate electricity. When the TMP plant runs at maximum capacity (i.e. both lines are running), the boiler steam use decreases (when compared to running the mill without load shifting) because there is more TMP steam production. This results in an increase of power production because more steam that is produced by the boiler plant is available to the turbines. Therefore, electricity load shifting has a negative effect on the amount of electricity that can be generated. However, this is outweighed by the profit that can be made by not producing TMP during peak hours. This is especially true if a real-time (or similar) pricing strategy is used [10].

Table 3: Impact of electricity load shifting on the mill-wide energy profile of an integrated newsprint mill when an alternative with increased DIP pulp production is implemented. The ratio of produced DIP and TMP pulp is 50:50

	Steam production boiler plant	Power production [a]	TMP pulp production	Boiler steam use [b]	Total power use [c]
No load shifting [d,e]	100	100	100	100	100
Load shifting [f,g]					
a. TMP plant shut down	100	90	0	110	50
b. TMP plant running	100	110	200	90	150

[a] may vary with cogeneration configuration
[b] boiler plant-produced steam used in the process
[c] power use for the whole mill
[d] all set to 100 to serve as a benchmark
[e] without load shifting, only one TMP line is in operation
[f] with load shifting, the TMP plant is shut down 50% of the time
[g] there are 2 separate TMP production lines

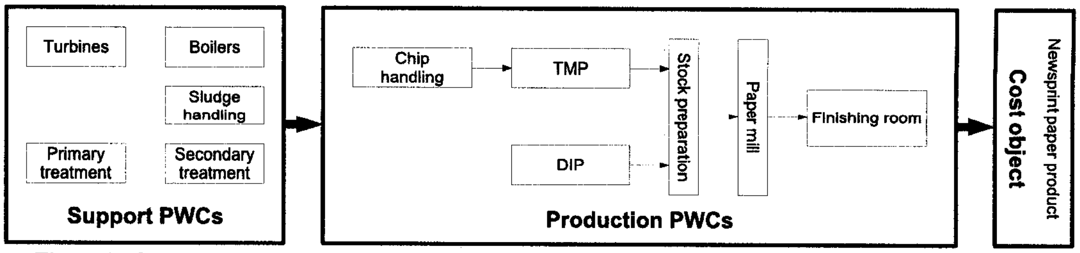

Figure 2: Cost categories and division of *PWCs* into production and support *PWCs* for a DIP integrated newsprint mill

METHODOLOGY

The methodology consisted of 4 major steps for each of the design alternatives as follows (see Figure 1) (see also see Janssen *et al.* [4]):

1. Calculation of total capital costs,
2. Calculation of mass and energy balances,
3. Modeling of and calculation of the manufacturing costs for the design alternatives with and without electricity load shifting using the operations-driven cost model,
4. Calculations for the evaluation of the design alternatives.

This methodology was implemented using the software package Impact: EDC™ from 3C Software Inc. [13].

Capital cost estimates & mass and energy balances

The total capital cost and the mass and energy balance models were constructed as described in Janssen *et al* [11]. A load profile for electricity load shifting was calculated considering on-peak and off-peak electricity price hours with average on-peak and off-peak prices, and constraints on the amount of TMP pulp that can be stored.

Operations-driven cost model

The process data provided by the mass and energy balances for each of the design alternatives were used as inputs for the operations-driven cost model. For the calculation of the variable costs, *Process Work Centres* (*PWCs*) were used to represent the processes that take place in the mill. The *PWCs* were divided into production and support *PWCs* (Figure 2). The overhead costs were calculated in the *Overheads Work Centre* (*OWC*). For more details about the construction of the model for this case study, see Janssen *et al.* [4].

Process design evaluation

Within the operations-driven cost approach, additional analyses were performed to characterize the design alternatives. Various profitability metrics were calculated to evaluate the feasibility of the design alternatives including Net Present Value (NPV) and Internal Rate of Return (IRR).

RESULTS & DISCUSSION

Evaluation of the manufacturing costs and profitability

The profitability of the design alternatives was estimated for the following conditions:

- Declining balance method for depreciation with a fixed depreciation rate. This rate was determined by considering the nature of each of the cost items in the capital cost estimate [14],
- Investment tax credit of $10/MWh of electricity produced by cogeneration based on renewable fuels [15],
- Generated power was sold to the grid at the nominal electricity price plus a 50% premium. This premium stimulates mills to sell their cogenerated power.

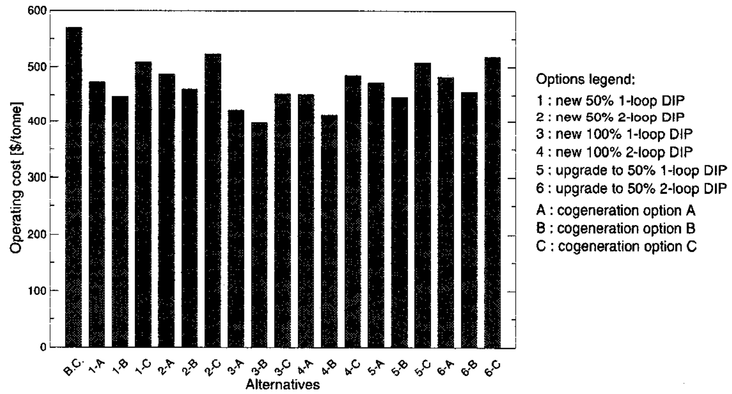

Figure 3: Total manufacturing cost per design alternative (including indirect costs but not including depreciation)

The manufacturing cost varied for the different process design options as summarized in Figure 3. The cost of depreciation has not been included in the calculation. All design alternatives have a lower total manufacturing cost than the base case mill. For a detailed discussion of the differences in total manufacturing cost between the design alternatives, see [4] and [11].

Based on the results of the profitability analysis (Figure 4), ten alternatives should be retained using the screening criterion of NPV>0 (and IRR>0). However, three more alternatives were discarded because they were only marginally profitable. Alternative 3-A appears to be the most profitable with an NPV of 82.3 M$ and an IRR of 8.1%. Sensitivity analyses were run to assess the impact of electricity prices on the profitability of the design alternatives (results not shown). Electricity consumption levels are lower in the design alternatives than in the base case, and therefore increased prices have a positive impact on the profitability of the design alternatives. If electricity prices were to increase by 100% for example, all of the design alternatives would generate a positive NPV.

Electricity load shifting in the TMP plant

An electricity load shifting profile for the TMP plant was calculated under the following conditions:

- The nominal on-peak and off-peak prices were determined from historical electricity data obtained from the IESO website [16],
- The on-peak price periods were from Monday to Friday from 7 am to 11 pm; the off-peak price periods were from Friday 11 pm to Monday 7 am and from Monday to Friday from 11 pm to 7 am,
- Both TMP lines were operated during up-time and were running at maximum capacity,
- TMP buffer tank capacity was 1000 BDMT, and tank level constraints were considered to be 10% for the lower level and 100% for the upper level,
- Paper production was 1100 FMT/day.

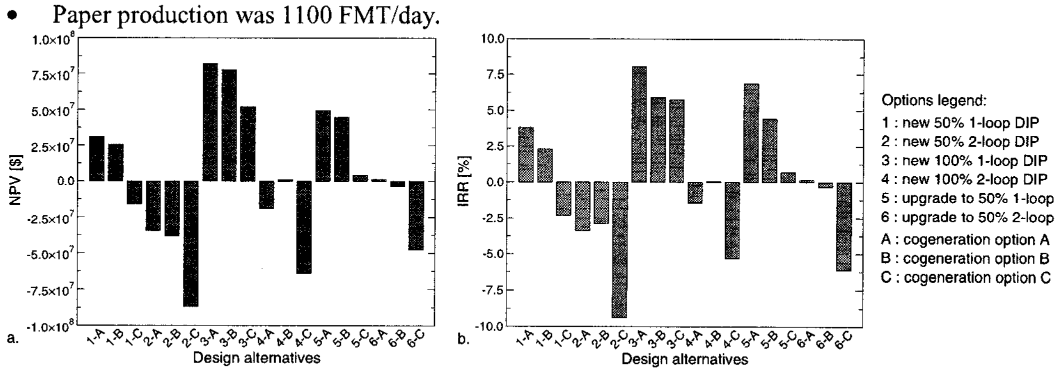

Figure 4: Profitability metrics for the design alternatives: a. NPV; b. IRR

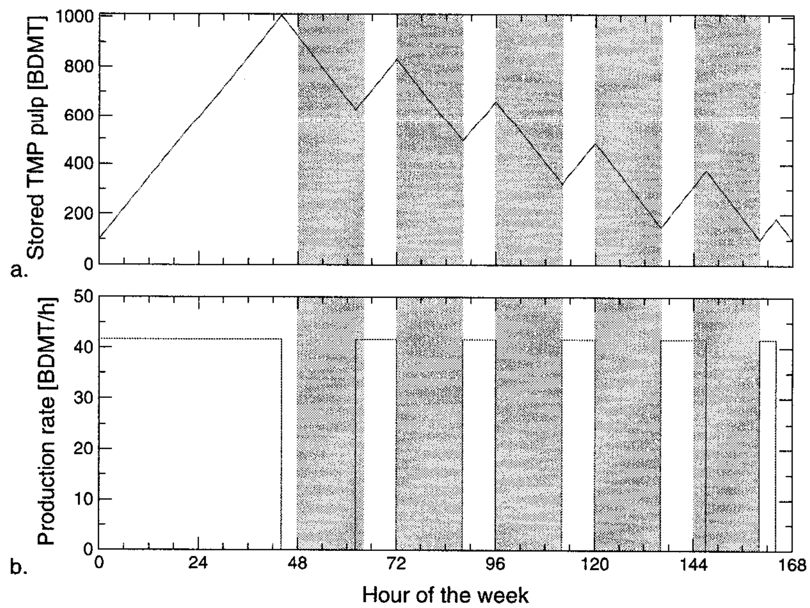

Figure 5: Electricity load shifting profile for paper production of 1100 FMT/day: a. amount of TMP buffered; b. production schedule

Grey areas indicate on-peak electricity price periods

Electricity load shifting was only applied to the alternatives that have 50% DIP pulp production, because the TMP plant was completely shut down in the 100% DIP alternatives. The average electricity price (in $/MWh) was calculated and used as the electricity price for the TMP plant. Only five hours of on-peak production were required during a period of one week to meet the TMP pulp demand by the paper machines and obey the buffer tank level constraints (Figure 5). This period could be further reduced with a somewhat larger storage tank providing additional buffer capacity.

The implementation of the load shifting profile results in an increase of the NPV of $21 to $27 million depending on the alternative. Two more design alternatives become profitable (NPV>0) (Figure 6). Alternative 3-A still is the most profitable, but alternatives 5-A and 5-B become more competitive. A sensitivity analysis was performed on the difference between the average on-peak and off-peak electricity prices to explore the impact of the

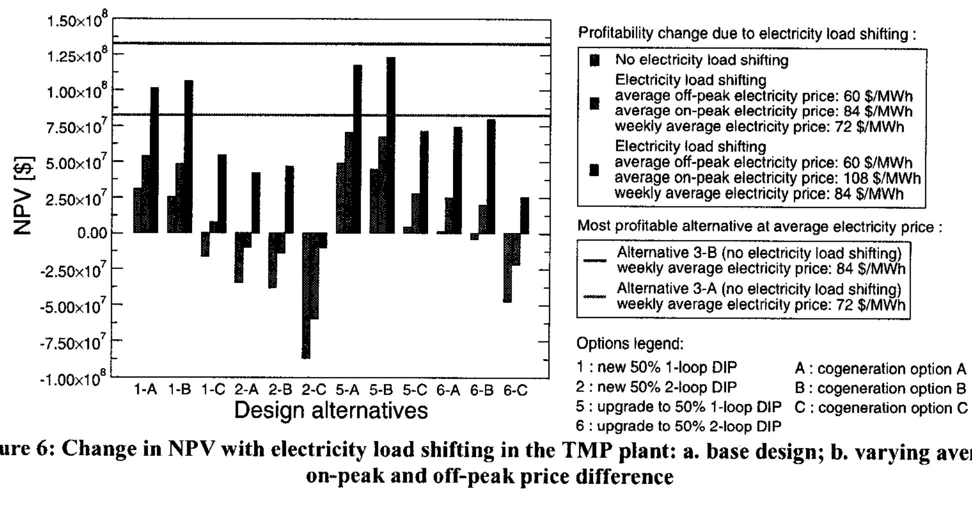

Figure 6: Change in NPV with electricity load shifting in the TMP plant: a. base design; b. varying average on-peak and off-peak price difference

Table 4: Total profit per day for alternatives 3-A and 5-A during 2 days with extreme price events (alternative 5-A with and without electricity load shifting)

Alternative	Date	Load shifting?	Newsprint price [$/FMT]	Profit existing mill [$/day]	Profit alternative [$/day]
3-A	03-Sept-02	No	735	$-2.0\cdot10^5$	$2.4\cdot10^5$
	30-May-06	No	745	$1.3\cdot10^4$	$3.0\cdot10^5$
5-A	03-Sept-02	Yes	735	$-2.0\cdot10^5$	$3.5\cdot10^5$
	03-Sept-02	No	735	$-2.0\cdot10^5$	$7.0\cdot10^4$
	30-May-06	Yes	745	$1.3\cdot10^4$	$3.8\cdot10^5$
	30-May-06	No	745	$1.3\cdot10^4$	$1.9\cdot10^5$

increased occurrence of electricity price peaks. Only the on-peak electricity price was varied. The results show that the greater this difference, the higher the NPV. Furthermore, at an on-peak electricity price of $108/MWh, alternative 5-B becomes the most profitable 50% DIP design. However, at this peak electricity price, a 100% DIP alternative remains most profitable (note that alternative 3-B is now most profitable).

Extreme electricity price events

To determine the implication of electricity load shifting during a day with an extreme electricity price event, two such days were chosen from the electricity price data available from the IESO website [16]. These days were September 3rd 2002, which had the highest peak electricity price since the deregulation of the electricity market in Ontario, and May 30th 2006, which was the most recent date with an extreme electricity price peak. The resulting manufacturing cost profiles were calculated for the most profitable 100% DIP alternative, 3-A, and for the most profitable 50% DIP alternative, 5-A. In choosing these two alternatives, the impact of electricity load shifting could be illustrated, since only alternative 5-A benefits from it. For each hour during these days, the manufacturing cost and the profit were calculated. For calculating the profit, a newsprint price of $735 CDN was used for September 3rd, 2002 and $745 for May 30th, 2006 [17] (Figure 7). Electricity load shifting in alternative 5-A decreases the manufacturing cost significantly (Figures 7d, i) and as a result, the profit per hour stays positive throughout the day (Figures 7e, j). Alternative 3-A exhibits a negative profit during the hours with the highest electricity prices on September 3rd, 2002, but a 100% DIP paper mill is much better able to deal with extreme electricity price events than the base case mill (Figures 7b, g and 8c, h).
The total profit per day for both alternatives increases sharply when compared to the existing mills during both days (Table 4). Alternative 5-A with electricity load shifting has the highest profit, while alternative 3-A has a higher profit per day than alternative 5-A without load shifting. This again demonstrates the ability of a 100% DIP mill to deal with an extreme electricity price event. Note that the newsprint price on Sept 3rd, 2002 was $475 US and on May 30th, 2006, it was $675 US. However, due to a much stronger Canadian dollar, the newsprint price in Canadian dollars only varied little between the two dates. The strength of the Canadian dollar has only a small effect on the profit of these two alternatives for the examined days, assuming the same market conditions and the same production rate for both dates.

CONCLUSIONS & IMPLICATIONS

This paper presented the application of a operations-driven cost model approach for a retrofit process design project at an integrated newsprint mill. The implementation of increased deinked pulp production and cogeneration was considered. Special attention was given to the evaluation of the impact of electricity load shifting on the profitability of the design alternatives. A model for the calculation of the cost benefits of load shifting was implemented in an operations-driven cost model.

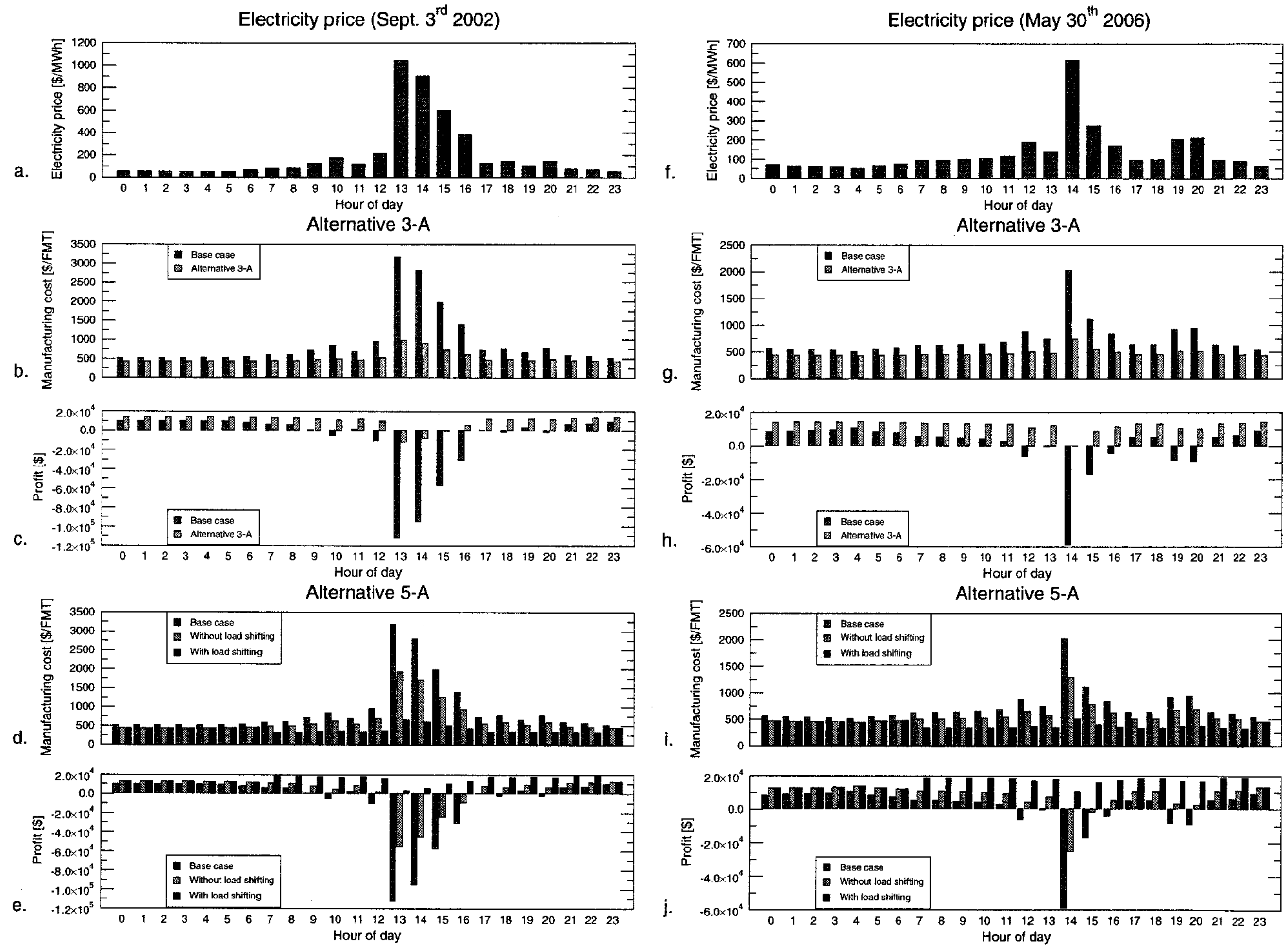

Figure 7: Manufacturing cost and profit for the existing mill, as well as alternatives 3-A and 5-A, with and without electricity load shifting during days with an extreme price event: a.-e. September 3rd 2002; f.-j. May 30th 2006

The initial profitability analysis revealed that a 100% 1-loop DIP alternative with increased wood waste capacity in the boiler plant was most profitable. Electricity prices and electricity load shifting had a significant impact on the profitability of the 50% DIP design alternatives and increased with \$21 to \$27 million depending on the alternative. The model outcomes suggested that considering electricity load shifting during the design stages may lead to different design decisions. This appeared to be more likely at high average electricity prices and a large difference between on-peak and off-peak electricity prices.
Load shifting was found to help mitigate the impact of extreme electricity price events. For instance, operating costs were reduced with \$2500/tonne when compared to the existing mill, at an extreme electricity price of \$1045/MWh. Furthermore, the strength of the Canadian dollar did not have a big impact on the total profit for the examined design alternatives during days with extreme electricity prices, assuming the same market conditions and the same production rate for both dates.
In this work, fixed on- and off-peak times were used to schedule the production of the TMP plant. However, more benefits may be realised if production is scheduled using mathematical optimization and considering real-time electricity prices.

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APPENDIX C

BACKGROUND ON C-LCA MODELING

Functional unit

The function that was defined for this analysis was the production and distribution of newsprint and the functional unit was the yearly newsprint production at the mill. The reference flow was the yearly production rate, i.e. 387200 admt (air-dried metric tonnes).

System boundaries and modeling of the system

The system boundaries and modeling of the system for the base case mill were based on those defined by Salazar (2004). However, several adjustment were made:

1. The collection and sorting of recycled paper were included within the system boundaries
2. The generic data used in this study were mostly extracted from the *ecoinvent 1.1* database instead of the Franklin database
3. The forestry operations were described using only secondary data, whereas before also primary data were used.

For modeling the consequences of the design alternatives, these boundaries were extended to include other affected systems. More specifically, changes in chip, wood waste and recycled paper flows necessitated an expansion of the system boundaries (see Table C.1). Also, changes in electricity consumption were modeled using the marginal technology (electricity generation by burning coal). Furthermore, a set of scenarios was defined in order to evaluate the performance of

Table C.1: Extension of system boundaries for base design alternatives and scenarios

Flow affected	Extension of system boundaries for base design alternatives	Extension of system boundaries for scenarios
Chips	Chip production in other systems and related forest operations	None
Wood waste	No system expansion required	Other wood waste users that have to compensate with another fuel
Waste paper	Waste paper landfill	Other waste paper users that have to compensate with virgin fibers and related forest operations

the retained design alternatives under different market conditions. The system boundaries were also adjusted for these scenarios (Table C.1).

Inventory results

All the generated flows were compiled in the SimaPro 7.0 LCA software. Table C.2 gives the most important inventory results for the base case mill. All substances that contributed more than 1% to each of the damage categories and the main unit process that causes the emission of the particular substance are mentioned.

For the calculation of the inventories of the design alternatives and scenarios, it was necessary to complete the available foreground inventory data (mill processes) with the most appropriate generic data for background inventory data (non-mill processes). For instance, if one alternative used a differential of +x kg of caustic (foreground data), the production of +x kg of caustic was modeled using generic data (background data). Most of the time, the generic data were taken from the *ecoinvent 1.1* database.

Table C.2: Inventory results for the LCA of the base case mill

Damage category	Substance	Contribution	Unit process
Human health	Dioxins	38%	Electricity, hard coal, at power plant
	Nitrogen oxides	25%	Electricity, hard coal, at power plant
	Particulates, < 2.5 μm	17%	Electricity, hard coal, at power plant
	Sulfur dioxide	14%	Electricity, hard coal, at power plant
	Radon-222	1.3%	Electricity, nuclear, at power plant
	Nitrogen oxides (as NO_2)	1%	Heat from natural gas
Ecosystem quality	Occupation, forest, intensive, normal	52%	Round wood, softwood, under bark, u=70% at forest road
	Zinc, ion	17%	Electricity, hard coal, at power plant
	Aluminum	15%	Electricity, hard coal, at power plant
	Nitrogen oxides	5%	Electricity, hard coal, at power plant
	Occupation, traffic area, road embankment	4%	Round wood, softwood, under bark, u=70% at forest road
	Aluminum	2%	Natural gas, at long-distance pipeline
Climate change	Carbon dioxide, fossil	97%	Electricity, hard coal, at power plant
	Methane, fossil	2%	Electricity, hard coal, at power plant
Resources	Uranium, in ground	46%	Electricity, nuclear, at power plant
	Coal, hard, unspecified, in ground	33%	Electricity, hard coal, at power plant
	Gas, natural, in ground	14%	Natural gas, at long-distance pipeline
	Oil, crude, in ground	7%	Transport, lorry 32t

Impact results

The impact assessment was carried out using the IMPACT 2002+ characterization method (Jolliet et al., 2003). In this method, the inventory results are linked via fourteen midpoint categories to four damage categories (human health, ecosystem quality, resources and climate change). In order to increase the comprehensibility of the results for decision makers, the impact assessment results were normalized using the initial life cycle environmental performance of the investigated newsprint mill (using a cradle-to-gate approach, i.e. from forest operation to distribution). A result of plus or minus X% indicated that the change in environmental impact caused by an alternative was equivalent to X% of the initial

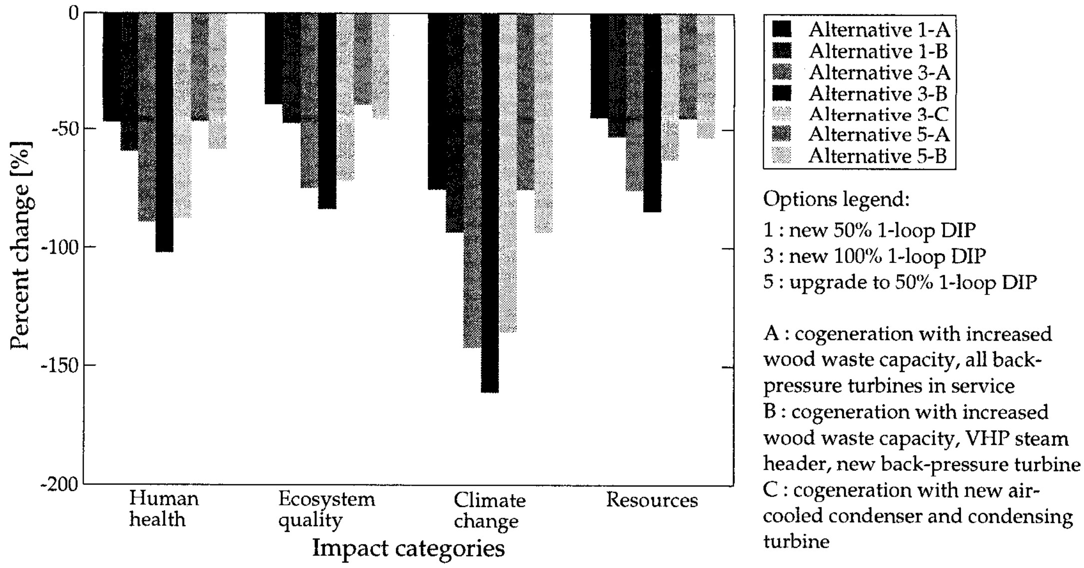

Figure C.1: Impact results of the LCA for the base design alternatives

life cycle environmental impact of the newsprint, the positive case indicating deterioration and the negative case improvement. Figure C.1 shows the results for the base design alternatives.

The utilization of the damage categories as decision criteria is very practical from a decision making standpoint compared to a midpoint method, because it involves a smaller number of indicators that are more meaningful for decision makers. However, endpoint methods generate more modeling uncertainties than midpoint methods (Bare, Hofstetter, Pennington, & Haes, 2000). For this case study, sensitivity analyses showed that the utilization of either of these sets of criteria (midpoint or damage categories) would lead to a similar decision most of the time.

Interpretation

Since this study was not focused on LCA but rather uses LCA results for demonstrating a broader methodology, no further interpretation was performed (e.g. sensitivity analyses or uncertainty analyses on LCA results).